Saving Lives with Generative Design and Agent-based Modeling

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The increasing number of crowd disasters has awakened the need to evaluate the evacuation performance of buildings. However, the information available in building design guidance documents is insufficient to efficiently address safety requirements and official metrics do not take into consideration crucial factors for the success of emergency evacuations, namely the people's dynamics. Although modeling human behavior is not trivial, the recent approach of Agent-Based modeling has been facilitating this task, thus being a suitable tool for evacuation simulations. Nevertheless, the potentialities of this approach are still quite unexplored. Although Agent-Based modeling is already being applied in security analysis tests, its use in combination with Generative Design (GD) is still very limited. In this work, we show how a combination of both approaches improves the safety of buildings.

Keywords: *Simulation, Agent-based Modeling, Agent, Evacuation, Performance-Based Design*

INTRODUCTION

Lately, architects have been taking advantage of programming to either extend the capabilities of their tools, or create new ones entirely (Kilkelly 2014). Generative Design (GD), a design approach that produces designs through algorithms, along with analysis and optimization, promote considerable advances in the design exploration process, and in the improvement of buildings' performance across different metrics, including structural, thermal, and environmental. While these metrics are important regarding the building's common use, there are others that also need to be considered in special situations, such as the case of an emergency. In these events, the way people behave and move constitutes a determinant factor, in addition to the local spatial characteristics. Nowadays, with the increasing number of crowd disasters, safety performance in public buildings becomes an important concern when designing a building. Realistic simulation of evacuations has been helping architects to understand and improve the buildings' safety measures. However, modeling human behavior is a complex task and the traditional simulation tools are not prepared to deal with it (Janssen 2005). Fortunately, the recent paradigm of Agent-Based Modeling (ABM) can handle complex systems, thus being a valuable tool for simulating human systems (Bonabeau 2002). For this reason, ABM is an important tool for modeling evacuation scenarios. Nevertheless, its application in architecture is still limited, being only applied at later design stages, when major changes are difficult to make. Although ABM has already been used as a GD method (Puusepp 2011), in this paper we use it in combination with GD, where GD generates the simulation scenarios, ABM is used to evaluate them, and the results used to influence the GD process, in an iterative cycle to improve a building's safety.

PERFORMANCE-BASED DESIGN

The design task is interdisciplinary, as each architectural project must integrate and satisfy the requirements from different fields (Turrin et al. 2011). Traditionally, only few of those requirements were considered in the conceptual phase of design, which mainly addressed aesthetical and functional performance criteria, postponing other disciplines to later stages of the process (Turrin et al. 2011; Shi 2010). However, it has been shown that decisions made in the initial phase have a great impact on the final solution performance. Moreover, at the final stage of the design process, there is usually not enough room for maneuver in order to efficiently address some of the requirements (Shi 2010), limiting the performance of the result.On the other hand, Performance-Based Design (PBD) is a design approach that combines the building's quantifiable performances with the functional and aesthetical requirements (Shi and Yang 2013). PBD arises from the integration of design synthesis with design evaluation processes, enabling the design process to diverge from a traditional paradigm - where the human subjectivity and rationality guides the process, and the performance evaluations are left for final stages - to one in which the design generation is oriented by analytical performance evaluations towards the objective of optimizing the design (Oxman 2008). Even though PBD only became successful in the last two decades, this concept is not new - it goes back to 1970, when Negroponte presented the utopian theory "Architecture Machine". Although research on Negroponte's concept was continued by other authors, it was only towards the end of the 20th century that PBD gained a boost of attention and application. This resulted from, firstly, the rise of sustainability awareness in the Architecture, Engineering and Construction industries (AEC), which encouraged the implementation of green building standards (Shi 2010). Secondly, from the proliferation of simulation tools. On the other hand, the advancements in GD have also played an important role in making PBD more accessible to architects. GD creates models that are based on associative geometry, i.e. a model with defined relationships between its elements that implies the establishment of a hierarchy of dependencies, where some attributes are independent - models' inputs - and others are dependent (Turrin et al. 2011). This chain of dependencies is responsible for the propagation of changes in a coherent way, a fundamental ingredient in the advancement of PBD. GD automates and accelerates the generation of design iterations, covering a larger design space, while replacing manual adjustments of the design geometry (Gerber et al. 2012).

EVACUATION

Panic behavior in crowd situations can be disastrous. Recent examples include girls being stampede in a stairway in Afghanistan in 2015, and the fire in a nightclub in Brazil in 2013. Mass events are a reality of our time and stampedes occur even without any physical trigger. In these situations, safety measures are determinant for the success of the event's outcome. While some measures are obvious, like the presence of fire doors and emergency exits, others are context-specific, such as the best location for those doors. Unfortunately, the traditional evaluation of different evacuation scenarios is either empirical or expensive (Wagner and Agrawal, 2014). Simulation through computation has the potential to overcome this problem since it allows the evaluation of different scenarios with less expenses. A simulation can be defined as an imitation of a real-world system (Banks et al. 1984), which requires the development of a simplified model of the system according to the investigation subject (Law and Kelton, 2000). Observing the model, we can estimate what would happen in the system and, by changing either the inputs or the geometric characteristics, we can also evaluate the effect of those changes. In fact, simulation is one of the most widely used tools in operations-research and system analysis, and it is also valuable for design (Banks et al. 1984). Initially, simulation programs were only developed for research, requiring a deep understanding, and, therefore, rarely used by architects. Nowadays, they have become more accessible and, aware of their advantages, architects and engineers started to integrate them into their workflow (Shi 2010). Currently, there are some simulation programs that cover several disciplines and, in this work, we are especially interested in simulating and evaluating the evacuation performance of public buildings.

AGENT-BASED MODELING

Agent-Based Modeling (ABM) is a simulation modeling paradigm that started gaining popularity in the 90's (Heath et al. 2009). Its attractiveness relies on the fact that it allows the simulation of systems that have complex interdependencies (Macal and North 2009). In ABM, systems are modelled as a collection of individuals, known as agents, which behave following a set of rules. Actually, the key factor of ABM is the ruled interaction between the agents (Janssen 2005), since the system's global behavior emerges from it (Bonabeau 2002). The sophistication of the model depends on the given rules - the agents' behavior can range from the most primitive to the more complex ones that already include learning and adaptive algorithms (Macal and North 2005). Through these, agents behave in accordance to their specific context, which allows the simulation to consider a heterogeneous sample instead of forced generalizations.ABM is becoming widespread, being the subject of intense study and development, and is also being applied to a vast variety of subjects, covering human social, physical, and biological systems (Macal and North 2009). Examples include the modeling of ancient civilizations (Chliaoutakis 2014); air traffic control (Conway 2006); and also land market (Filatova et al. 2011). ABM is a suitable approach to deal with crowd and evacuation systems and, combined with the advances in computational power, it has been enabling the simulation of more complex systems. Some of the recent studies include crowd evacuation of buildings and urban roadways (Wagner and Agrawal 2014), evacuation from a foot bridge (Carroll et al. 2012), or from a train station under a bioterrorist attack (Wei et al. 2011). Nevertheless, due to the variety of potential disaster environments that may occur, the use of ABM in emergency planning remains an open research area (Jain and McLean 2008). The main difficulty found when dealing with ABM is acquiring the appropriate data to construct the models. Regarding human behavior, most of the research in matters of panic is of empirical nature (Helbing and Farkas, 2002) and, in relation to the overall system behavior, there are not yet systematic studies or quantitative theories (Helbing et al. 2000). This lack of information makes the model's calibration and validation difficult to achieve. Still, there are already some important contributions to the field. Helbing (2000) modeled the collective phenomenon of escape panic based on socio-psychology literature, media reports, and other indirect methods. More recently Bellomo et al. (2016) made an overview of the study of human behavior in evacuation, where they also addressed the validation that most authors dismiss.As shown by Bonabeau (2002), ABM is a valuable tool for simulating human systems, and Procházka et al. (2015) demonstrated that programming pedestrian and crowd dynamics is relevant, specially, when its overall success has a lot to do with the users and their behavior. ABM appears to be a promising tool to solve circulation problems, in which agents represent the individual dynamic behavior in a built environment. In fact, pedestrian movement, evacuation and crowding models have been the main focus of ABM's in architecture (Puusepp 2011).

ABM-GD FRAMEWORK

Even though most agent-based models are analytical, there are applications of this paradigm with GD processes: Puusepp (2011) studied the use of multi-agent systems for generating circulation diagrams; Reffat (2003) developed a model where agents generate new design concepts by exploring two-dimensional sketches.Nevertheless, although ABM has been used as the driver of a GD process, it has not yet been explored as being driven by a GD process. By this we mean a PBD approach that combines GD and ABM, which is opportune at different levels. Firstly, GD is appropriate to generate complex designs in which the performance is difficult to predict, especially when considering the human behavior. Thus, a simulation tool that can encompass the GD paradigm is convenient. Secondly, GD has been mostly used in public buildings, such as stadiums, office buildings, and museums, where safety requirements are especially relevant, including the emergency evacuation performance. Therefore, a tool for safety performance evaluation is particularly valuable, which is the case of ABM. Finally, instead of only using ABM to analyze the obtained solutions in terms of evacuation safety, we propose that ABM can also be used to improve the design towards a better solution regarding its safety metrics, while considering its geometric and aesthetical basic requirements. This possibility is enabled (1) by the capability of ABM to simulate and evaluate the evacuation times of several design variations, and (2) by the flexibility of GD, which allows changing the model in an automated way and according to the information acquired from the simulations.

CASE STUDY: PARAMETRIC SHOPPING MALL

In this work, we present a combination between GD and ABM in a Performance-based approach. Based on it, we developed a case study using GD that allows the generation of several instances to be then evaluated through a simulation process - in this case the simulation of an emergency evacuation. Our goal is, firstly, to compare the input parameters of each evaluation and its corresponding results - numerical and visual results - and, secondly, to acknowledge trends and behavior patterns through this balance. Thus, this allows the subsequent generation of new variations for the model through an optimized perspective, by repeating the cycle *generation-simulation-evaluation* and, therefore, achieving improved design solutions.

Geometric Definition

We started by developing a GD model of a simplified shopping mall. The model corresponds to a single story quadrangular building in which the stores are placed in concentric rings around a central atrium. From this atrium, a set of main corridors breaks the rings and gives access to the building's exits. A concentric ring corridor is also placed between rings of stores (see Figure 1). Figure 2 summarizes the model's parameters, which are:

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

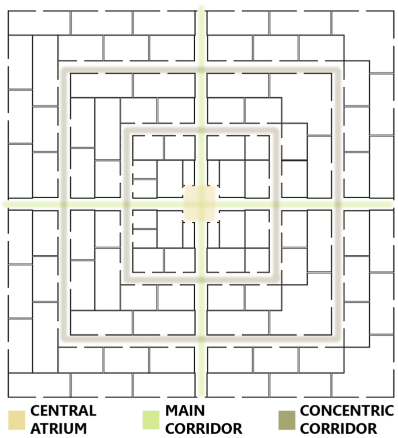

Figure 1
Instance of the parametric model with its basic structure marked.

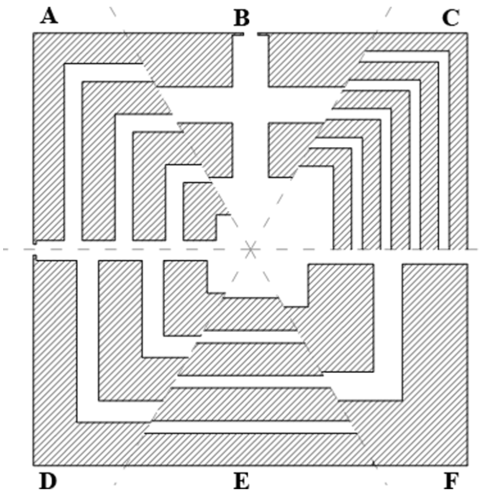

Figure 2
Potential automatic variations of the model: number of concentric corridors (as an example, A has three concentric corridors, while B has one); width of corridors (for instance, C has the smallest width value of all, whereas B has the biggest); area of the central atrium (C has the largest central atrium of all examples); and the number of main corridors (the vertical axis in example E is closed, i.e., it does not have a main corridor connecting the outside with the mall's central void).

Simulation Process

The next step was generating a representative solution space. 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 GD capability to easily create a substantial solution space, we evaluated variations of one parameter, while maintaining the others unchanged, and 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.

To evaluate the models, from the current available simulation tools (Cuesta et al. 2015; Peacock et al. 2010) we selected *Pathfinder*, as it adequately satisfied the requirements of our scenario.

Emergency Evacuation Results

Finally, after executing all the simulations, we organized the simulation results into a set of graphs - see Figure 3. The vertical axis in all the graphs correspond to the evacuation times in seconds, whereas each horizontal axis corresponds to the input variable being considered - width of corridors, shops' doors, and exit doors; number of concentric ring corridors, and main corridors; size of the mall's central atrium. Finally, the curves of different colors correspond to different numbers of users.

Figure 3A shows the outcome of the variable *number of concentric corridors* for the values 1 to 4. It shows that this variable's variation has impact in the evacuation times, even though it can be quite smooth in certain situations, as is the case of smaller numbers of users. However, as this number increases, the evacuation times also increase, and more significantly regarding higher numbers of concentric corridors. Regarding the second analysis in Figure 3B, which evaluates the variable *exit doors size*, it is possible to understand that this is a critical variable in this model, since its variation causes meaningful changes in the performance results - except in the case of very few users, where the evacuation times remain almost constant. Figure 3C presents the results of the variable *number of main corridors*. This variable received three different values as input: 2, 3 or 4 main corridors. Since these are the corridors that give access to the mall's exit doors, it means that, by decreasing the number of corridors, we are automatically decreasing the number of exit doors. As it is visible in Figure 3C, the evacuation time increases with the decreasing number of main corridors, and it gets more accentuated with higher numbers of user densities. Otherwise, all evacuation times seem to converge as the number of corridors increases. Figure 3D presents the evaluation of the *central atrium size* variable, from which it is possible to conclude that it almost does not interfere with evacuation times for all user density values.The results regarding the "corridors width" variable are shown in Figure 3E. The width varied between 2.5 and 5.5 meters, with incre-

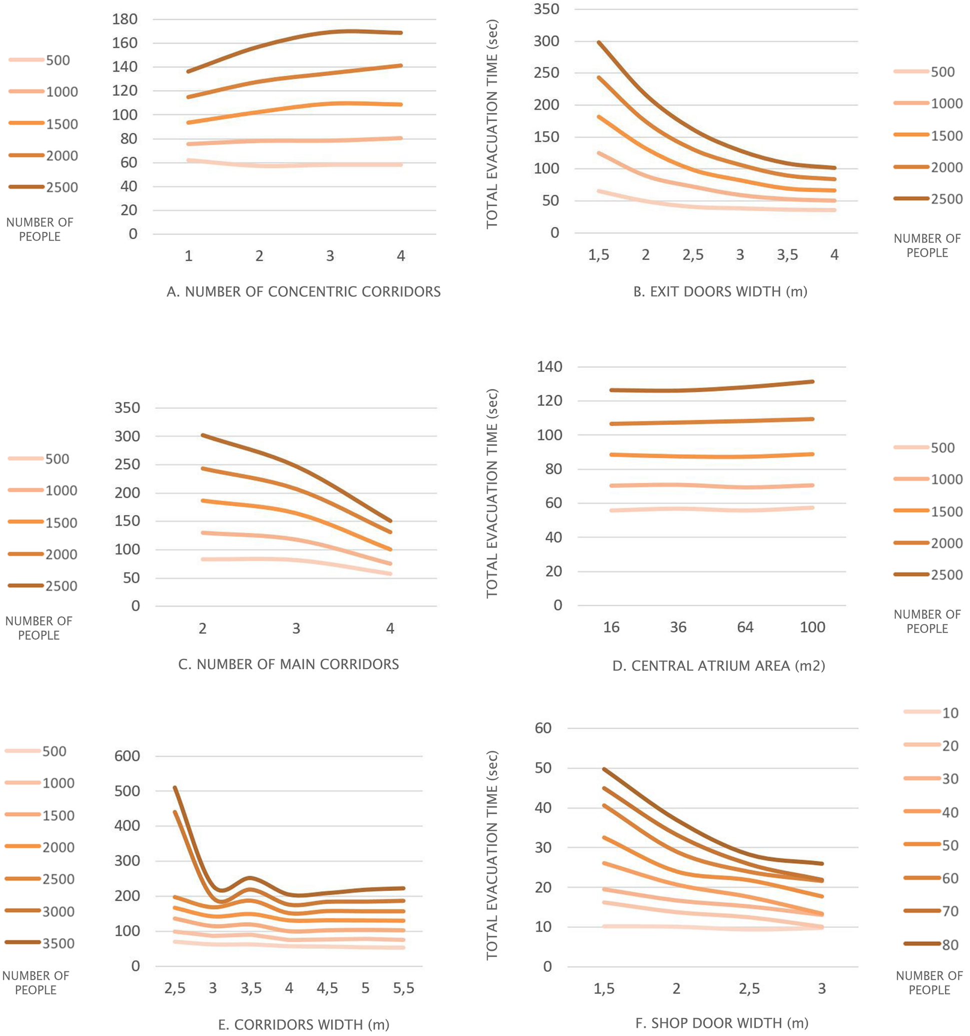

Figure 3
A. Evacuation time for different numbers of concentric corridors; B. Evacuation time for different widths of exit doors; C. Evacuation time for different numbers of main corridors; D. Evacuation time for the central atrium different areas; E. Evacuation time for different corridor widths; F. Evacuation times from a single store with different door widths (the number of people inside the store varies between 10 and 80).

ments of 0.5 meters. Even though the width variation has almost no impact in evacuation times for smaller numbers of people, as this number grows, the graph's behavior becomes irregular - it does not decrease linearly, instead it grows and decreases with consecutive values. Finally, we tested the effect of changing the *stores' door size* between 1.5 and 3 meters (Figure 3F). This simulation occurred in slightly different conditions comparing to the previous examples, since it measured the time people took to get out from a single store, instead of the whole shopping mall. To maintain the user density, we simulated a smaller number of users. Nevertheless, as previously demonstrated by the evaluation in example B, door widths are key points on emergency evacuations, especially with higher concentrations of people.

RESULTS

From an overall analysis point, we can make significant conclusions regarding higher numbers of people. Globally, as the number of people increases, their effects 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. As an example, Figure 3B shows that the exit doors' size has a great impact on the evacuation performance, whereas Figure 3A reveals that the variable *number of concentric corridors* only becomes relevant after a certain number of people is reached. Finally, Figure 3D shows that the variable *central atrium area* has almost no effect on the evacuation times. Although some variables revealed trends in behavior, such as the variables visible in Figure 3 B, C, D and F, others have a more complex and unpredictable behavior, as is the example of Figure 3E. 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. Therefore, the designer should consider these non-linear phenomena in order to gradually improve the design solution. In the next sections we analyze two of these situations.

Corridors Width

Changing the corridors' width seems a sensible action to improve the evacuation performance but one should also consider that when we increase the corridors' width, their lengths also decrease, meaning that two geometric characteristics are changed instead of one. Moreover, although changing the corridors' width may help alleviate intersection areas, it can also create obstruction problems at the exit points, since the users reach these areas more rapidly. Analyzing the results, it is possible to understand that when the corridors are too thin, people get jammed in the intersections and, thus, do not reach the exit doors (Figure 4A). On the contrary, when corridors are too wide, people get stuck in the exits (Figure 4C and 4D). In intermediate situations, such as the case of Figure 4B, there is a balance between people getting stuck in the intersection points and exit doors. This divided flow rate allows a better coordination between users' evacuation routes and, thereby, a better evacuation time. In addition, the length and thickness of the corridor that connects the two critical points contributes to the balance of the flow rate.

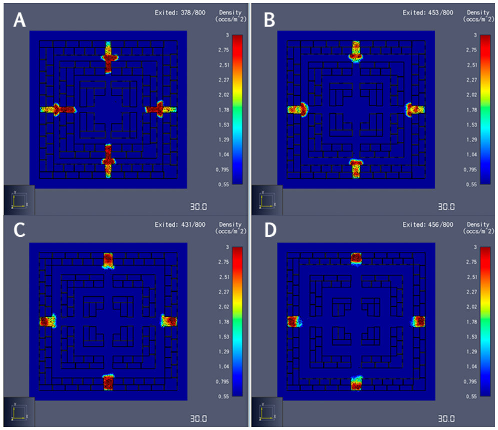

Figure 4
User density levels (for 1500 visitors) at 45 seconds of the evacuation time. Each diagram corresponds to different corridor widths: A=2,5; B=3,5; C=4,5; D=5,5 m. Colors show the density of people.

In the previous example, the corridors' width was varied while the size of the exit doors was kept unchanged. Considering the critical influence of the exit doors' size in this balance, we decided to further analyze the impact of varying the corridors' width accompanied by exit doors' of the same size. The results are visible in Figure 5, from which we could conclude that when the exit doors size have the same width as the corridors, the evacuation performance turned out to be more linear.

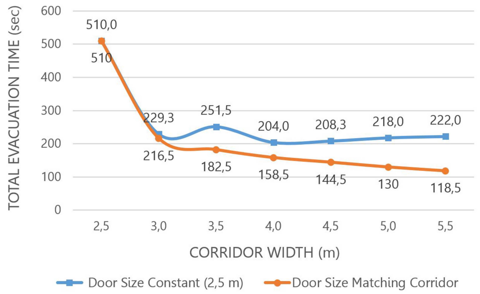

Figure 5
Comparison between changing the corridors' width using fixed exit doors' size and using exit doors whose size matches the size of the corridors.

CORRIDOR AND DOOR SIZE (m)		3	4	5
N CONCENTRIC CORRIDORS	2	156	123,8	**101**
	3	157,3	125,8	103
	4	**160,5**	129,8	103,3

Table 1
Evacuation times for different number of rings, corridor widths, and exit door size (for 2500 visitors). The results are in seconds. The values in bold represent the maximum and minimum evacuation times.

Number of Concentric Corridors
We also analyzed the results obtained from the *number of concentric corridors* variable (Figure 3A). As shown previously, there is an irregularity in these results, regarding the number of rings and the corresponding evacuation times of different numbers of people. In practical terms, the effects of increasing the value of this variable has impact on the evacuation times because (1) it increases the number of intersections areas, which can work as filters so that people are not all in the same place, decreasing the evacuation times (see Figure 6), (2) it decreases the length of the corridors that cross the stores - long corridors can distribute people, whereas short corridors concentrate them, and (3) it narrows the corridors - small corridor widths potentiate the obstruction of people, thus increasing evacuation times.Moreover, as shown in the analysis of Figure 3E, when corridors are too narrow, the intersection areas become critical points (see also Figure 6B). In that line of thought, we further explored the relation between the number of concentric corridors and different corridor widths (visible in Table 1), and, based on the previous analysis (Figure 5), the exit door's size matching the corridor's width. This analysis shows that the evacuation performance is better for a smaller number of rings.

Regarding the modeled shopping mall, the simulations allow us to conclude that we should:

- Minimize the number of concentric corridors;
- Maximize corridor's width;
- Use exit doors with the same width as corridors;
- Maximize transversal corridors;

CONCLUSIONS
Architects are increasingly more interested in designing safe architectural solutions. PBD is a design process that emphasizes the building's performance. It consists of cycles of *generation-evaluation-analysis* from which the architect can gradually achieve better performing solutions. It is an iterative process in which each cycle requires the generation of a solution whose evaluation and analysis is the basis for the next iteration. For the analysis to be successful, it is necessary that the generated and evaluated solution space is substantial in terms of number and quality, and the acceptable number of cycles depends on each model complexity. In this paper, we demonstrated the feasibility of the combination of GD and simulation in a context of PBD, where evacuation performance is the focus. The relevant role of human behavior implied the integration of ABM in this study. To evaluate the combination GD-ABM, we developed a case study based on a generative approach - a shopping mall - and, then, we produced several evacua-

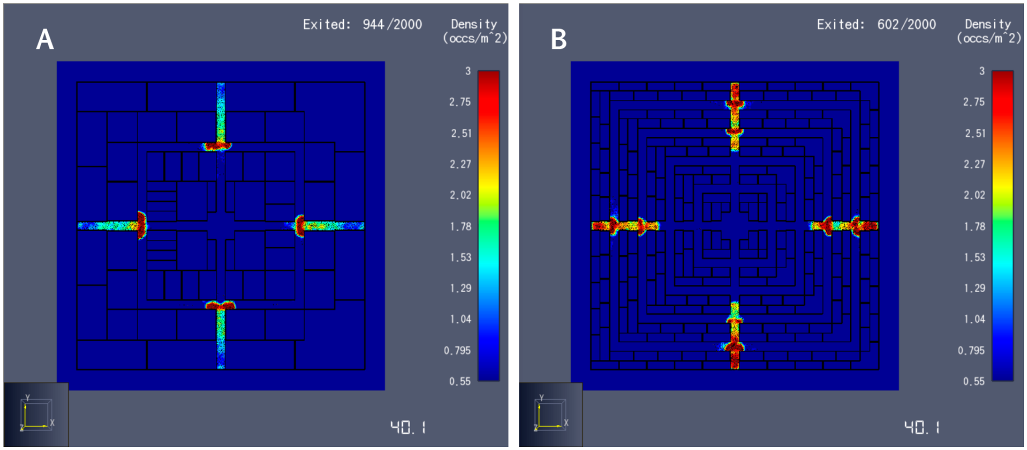

Figure 6
Densities for different number of rings.

tion simulations regarding different parameters, such as doors' width, area of the central atrium, and number of corridors. The use of GD enabled the generation of different instances of the model more rapidly and in an automated way - by changing the parameters, the model was automatically adapted - allowing us to cover a wider design space than if we used a traditional design approach.The case study demonstrated that the use of GD potentiates PBD. By allowing the consideration of wider solution space, it potentiates better results. Based on the results' analysis it is possible to make more pertinent combinations of parameters for future iterations, thus accelerating the search for improved solutions. Even though the simplicity of our case study, it could already demonstrate that the influence of certain parameters in the building's performance is not trivial to predict, revealing the relevance of additional tools to support the decision-making process. In real scenarios, where the scale and the complexity of the building increase, there are more inter-dependencies between parameters and, thus, the architect intuition might not be enough. Hence, it will be even more necessary to resort to a design process that is based on numerical evaluations and analysis.

ACKNOWLEDGEMENTS
This work was supported by national funds through Fundação para a Ciência e a Tecnologia (FCT) with reference UID/CEC/50021/2013.

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