The Effects of Human Behavior Simulation on Architecture Major Students' Fire Egress Planning

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Abstract
This study examines the previously unknown relationship between using human behavior simulation, equipped autonomous, intelligent Virtual-Users, and students' self-experimentation performance in fire egress planning. The research method involved 70 students in authentic design courses who proposed floor plans for office buildings before and after simulating evacuee behaviors. They then scored their experiences based on using the simulation. Statistical analysis of those scores reveals that using human behavior simulation helps students find unexpected problems, evaluate the validity and functionality of design solutions, conduct the experimentation process more efficiently, and determine the solutions with relative ease. The main reasons for these results are posited to be the explicit, analytic, and observable representation of virtual evacuees, their manipulative parameters, and an integrated system between human behavior simulation and Building Information Modeling (BIM). The findings of the present study can contribute to developing a rational computational means for education in fire egress planning.

Keywords: human behavior simulation; building information modeling (BIM); fire egress planning; architectural design education; virtual users

1. Introduction
As high-rise buildings and mega-sized architecture become ever more common in many built environments, the importance of fire egress planning is receiving greater emphasis in architectural design education. Fire egress planning demands rigorous and rational analysis of and experimentation on the relationship between users' evacuation behaviors and the physical layouts of the proposed buildings, but in reality, design studio education still relies largely on abstract assumptions and extrapolation methods like fire evacuation norms, regulations, and analysis of previous cases (Frantzich, 1994; Hadjisophocleous, Benichou, & Tamin, 1998). While the advent of virtual reality technology allows for the evaluation of direct experience, setting up that equipment requires funding, space, and participants, so the method is expensive to use in empirical architectural design studios (Gwyne et al., 1999; Kalay, 2004; Sun & de Vries, 2013).

To deal more effectively with the analysis and evaluation methods in fire egress planning, simulation methods have been proposed in the fields of environmental psychology, computer science, and architecture. The rationale for simulation methods rests on providing experimental conditions amongst variables in fire egress (Simon, 1999). Especially in human behavior simulations, users' actions are computed and generated in response to the proposed physical properties of buildings; as a means of experimentation, this method allows for iteration of all possible relationships between the properties of autonomous agents and environmental conditions (Chu, Parigi, Law, & Latombe, 2014b; Kalay & Irazabal, 1995). The simulation also provides analytic and observable representations that describe the complex dynamics of prospective occupants (Ekholm, 2001; Hong, Schaumann, & Kalay, 2016). Based on the characteristics of the specific simulation method, recent studies have highlighted the potential usability of human behavior simulation in analyzing and predicting pedestrian safety and circulation patterns (Jalalian, Chalup, & Ostwald, 2011), occupant workloads (Tabak, de Vries, & Dijkstra, 2010), and social behaviors during fire egress (Chu, Parigi, Law, & Latombe, 2014a). From the pedagogic viewpoint, human behavior simulation is an effective method that facilitates the cyclic design developments of architecture major students (Hong et al., 2016). However, previous studies, especially in fire egress simulation, focused mainly on computational models of human behaviors (Pan, Han, Dauber, & Law, 2006; Pelechano & Malkawi, 2008), and data distribution and structure (Goldstein, Tessier, & Khan, 2011; Simeone,
Kalay, Schaumann, & Hong, 2013). Still unknown are the effects of human behavior simulation on students' problem finding and decision making in fire egress planning, which the present study investigates. The remainder of the paper is structured as follows: Section 2 reviews the human behavior simulation methods applied in fire egress planning, Section 3 elucidates the research methods of the present study, Section 4 reports the results of the statistical analysis, and Section 5 interprets the results and offers further discussion.

2. Literature Review

2.1 Planning Methods in Fire Egress Planning

Architectural planning is a cyclic refinement designed to lead to the desired performances of physical layouts in different contexts (Rittel, 1971). It involves analyzing and evaluating the performances of physical layouts and requires resources and evidence for appropriate decision making (Goldschmidt, 2014; Rowe, 1996). In fire egress planning, the analysis of hypothesized physical layouts is critical to supporting safe evacuation routes; rigorous decision making using valid planning methods is thus of central importance, because those methods impact the ways in which planners discover unexpected side effects of building layouts and confirm the tested performances of solutions (Rittel, 1971).

In authentic fire egress planning, regulation-based calculation and extrapolation are the most common methods chosen by architects and planners. Calculation is based on generalized norms and atomic standards, while extrapolation stems from deduction using past experiences and cases. Therefore, both methods are limited in their utility for any new building layouts beyond known norms, standards, and past cases (Kalay, 2004). To overcome the shortcomings of these traditional methods, several pioneering studies have highlighted the application of advanced simulation technology to experimenting with hypothetical relationships between novel proposed building layouts and evacuee behaviors (Chu et al., 2014a; 2014b; Pan et al., 2006; Pelechano & Malkawi, 2008; Xiaoping et al., 2009). These simulation methods are particularly useful when the relationships amongst decision variables are too complex, conflicting, or dangerous to test in reality. For instance, Sun, and de Vries (2013) applied a 3D immersive virtual environment to investigate the relationship between the physical properties of exit doors (width, height, side of exit door relative to evacuee's location, angles from view direction, and orientation in the layout) and exit door selection behaviors in fire evacuation. However, while this direct experience simulation method captures micro-perceptions and subtle behavioral responses of actual examinees, it is also limited because of the expense, space, and techniques needed to construct experimental settings and recruit massive numbers of human examinees. In that study, the authors also reported that examinees' responses may differ from those of actual users due to stress and the quality of the stimuli employed. As a radical approach to simulate evacuees' behavior in built environments, Kalay et al. (1995; 2004) developed the concept of autonomous, anthropomorphic, rational computer agents, called VirtualUsers (VUsers). VUsers are equipped with simulated sensors to make them aware of physical and social stimuli and can generate probable behavioral responses according to social and cultural behavioral patterns. VUsers generate their behaviors according to a set of goals and rules. The simulation method using VUsers, known as human behavior simulation, has been applied to analyzing office workers' activities in a specific organization and the spatial layout in which activities take place (Tabak et al., 2010), the comprehensive use processes of hospitals (Simeone et al., 2013), and pedestrians' walking routes (Jalalian et al.; 2011). The potential of this simulation method has also been highlighted in previous fire egress planning studies, as detailed below.

2.2 Human Behavior Simulation in Fire Egress Planning

To simulate massive numbers of evacuees, previous studies focused on investigating computational models of human behaviors. For instance, Xiaoping et al. (2009) introduced and categorized behavioral models to simulate evacuees from discrete cell-based path findings to bottom-up interactions between autonomous agents. The authors noted that recent approaches had adopted mixed behavioral models to reflect the heterogeneous behaviors and psychological mechanisms of evacuees. Pelechano & Malkawi (2008) examined the applicability of a grid-based pathfinding model, called cellular automata, for fire egress simulation, suggesting that the grid-based evacuation model should be improved to simulate the body-to-body bottlenecks observed in actual emergency evacuations and the parameters of evacuees' flow rates, while speeds should be iterative rather than using pre-defined values.

In addition, from the perspective of the social behaviors of evacuees, Pan et al. (2006) implemented an autonomous multi-agent model that simulates individual agents' locomotion and steering behaviors, the interactions among individual agents such as body-to-body competitive behavior, queuing behavior, herding behavior, and bidirectional crowds. Chu et al. (2014a; 2014b) developed SAFEgress, a social agent-based egress simulation model that computes occupants' intimacy vis-à-vis social groups, social structures, and social norms.

While previous studies highlighted the improvements of evacuee behavioral models and parameters, it was equally important that these studies all support the decision making of architects and planners. Through the use of human behavior simulation, they demonstrate that it is possible for architects and planners to direct the dynamic and descriptive behaviors of evacuees in
the 3D virtual environments in which they are placed to analyze the safety of proposed buildings with regard to intended evacuee behaviors. However, despite the advanced computational models of evacuees, the effects of human behavior simulation on decision making and self-experimentation among architects and planners in fire egress planning remain unknown.

Investigating these effects is especially important in the field of architectural design education. Schools of architecture have recently emphasized training students to conduct fire egress planning as a core competence of professional architects. However, in reality, traditional methods such as regulation-based calculation and extrapolation are limited in their exploration of unexpected phenomena and fluent experimentation for the students. In addition, from the perspective of authentic education, direct experience simulation is also an expensive method that involves recruiting actual participants and setting up equipment. Therefore, the use of a human behavior simulation method that allows students to explore and iterate matches between the physical properties of buildings and the parameters of evacuees has been proposed (Hong et al., 2016).

To teach and manage fire safety planning, Wang et al. (2015) developed a BIM-based analysis and evaluation system that computes the escape distances and times required to respond to a given BIM model and checks the match between fire escape performance and fire evacuation regulations. The system's camera walkthrough captures a simulated escape route that can be used for fire safety education. The authors found that a 3D representation of the evacuee’s view is useful for perceiving the locations of equipment. However, in that study, while the implemented system stems from the direct experience simulation method, it involved actual human users rather than simulating the behaviors of complex, massive numbers of evacuees.

From an educational perspective, Hong et al. (2016) discovered that both analytic experimentation and observable representation of human behavior simulation enable students to iterate matches between goals and potential solutions and the parameters of VUsers to examine the complete performance of ultimate solutions under what-if scenarios [Fig.1.]. The authors also stated that observing the detailed behavioral performance of heterogeneous VUsers inspires students to discover the unexpected physical appropriateness and social implications of design solutions. Ekholm (2001) also noted that representing occupants' activities in building spaces supports the functionality analysis of buildings.

Fire egress simulation was also applied to train occupants of a building in personal fire safety skills. Chittaro and Ranon (2009) developed a virtual reality simulation platform that represents serious conditions in a fire evacuation scenario. The authors simulated the physical layout of a building, including walls and exits, and revealed the emergency situations of a building to occupants who lived in the building. They tested this platform in order to reduce critical evaluation times and captured aggregated patterns of real-world occupants. Rüppel and Schatz (2011) shared this aim and also developed a serious human rescue game. They used BIM and a commercial game engine to represent smoke and fire, and applied the platform to evaluating fire evacuation performance at the phase of conceptual design.

While previous studies have argued for iterating the physical layouts of buildings to match the parameters of VUsers, using advancing modeling tools such as BIM and observing their represented behaviors using a 3D game engine to support student experimentation and decision making, they involve qualitative interpretations, so generalized statistical effects of the simulation for educational uses have not yet been proven. In addition, from the technical point of view, a simulation tool that combines the advantages of BIM, such as rapid synthesis and modification of building layouts, and 3D game engines, which represent the behaviors of VUsers, has not been implemented in the students’ practical, real-world fire egress planning.

3. Research Questions

The present study thus aims to investigate the effects of human behavior simulation on students' self-evaluation and discovery in fire egress planning. Specifically, the study answers the following research questions: (1) When using human behavior simulation, do students discover more unexpected problems in alternative solutions to fire egress planning than without simulation? (2) When using human behavior simulation, do students have confidence in evaluating the usability and validity of the results of the fire egress planning more than they do without the simulation?
(3) When using human behavior simulation, do students conduct and experiment with processes of fire egress planning more efficiently than they do without the simulation? (4) When using human behavior simulation, do students determine the optimal design results of fire egress planning more easily than they do without the simulation?

To investigate these questions, this study adopts a quantitative research method that compares students' evaluation and discovery scores as collected in experiments in which students either use or do not use the simulation. For comparison, a human behavior simulation platform is developed and added to a commercial BIM tool. The platform allows students to create and modify a building model with the BIM tool and to populate heterogeneous VUsers into the BIM model. The following section lists the present study's methods and procedures in detail.

4. Methods
4.1 Comparative Case Study
A total of 70 students – 32 in fall 2013 and 38 in fall 2014 – participated in a computer-aided architectural design course called Digital Design Lab. They were all third-year university students at H University in South Korea whose major was architecture, a five-year professional program. All had completed five semesters of design studios and courses before the course in this study. The course curriculum was the same in the 2013 and 2014 fall semesters, as was the instructor. The method of teaching and the process of learning were also equivalent.

As the main design project in this course, students developed an office building with a maximum of 20 stories on the given site of 50 x 70m. In the fire egress assignment, students were asked to design and develop one standard floor of that office building. They were also asked to satisfy a South Korean fire evacuation law requiring that evacuees' routes of egress would be less than 50m, as measured from any standing points on the floor to the planned exits. In one week, the students used the Autodesk Revit, a commercial BIM toolkit, to plan and refine the locations, dimensions, and number of fire exits assumed to be located on a standard floor of the building. In this process, they used calculations, relying on the law's stipulations, to approximate the behavior of evacuees in the proposed floor layout.

In the following week, the students used a human behavior simulation platform called SafeBIM that was integrated into the BIM toolkit to analyze the routes, distances, and times of evacuees. They then refined the previous floor layout according to their analyses (Fig.2). In order to maintain consistency for this study, all students in 2013 and 2014 used the same version of SafeBIM. After completing the fire egress planning tasks, the students completed the survey questionnaire presented in Table 1. The questionnaire used a seven-step Likert scale (0 = not at all, 7 very much), and asked students to list (1) all problems that they discovered in the simulation, and (2) the advantages and disadvantages of the simulation in examining their fire egress planning proposals. The proposed plans had to contain the locations, dimensions, and number

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<th>SafeBIM simulation</th>
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<td><img src="image2.png" alt="SafeBIM Simulation" /></td>
<td><img src="image3.png" alt="After Simulation" /></td>
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Fig.2. Examples of Fire Egress Planning before and after Using SafeBIM
of fire exits and the evacuees' routes. The collected qualitative data were used to determine the probable reasons for the results of the statistical analysis.

In the present study, comparisons before and after using the simulation platform were conducted in authentic design courses rather than lab experiments. The students used the simulation platform to produce weekly assignments, so they examined the applicability of the simulation for the given design tasks without extreme and artificial time limits. The assignment score based on the results and process records of fire egress planning also motivated students to concentrate on the given design tasks. Compared to lab experiments, the authentic case approach of this study reflects real-world phenomena; it is also valid in applications to world phenomena; it is also valid in applications to the authentic case approach of this study reflects real-


dynamic path-findings, locomotion, and body-to-

of paths initiates the steering behavior of agents. The locomotion and interactive behaviors of an individual agent can be also represented due to the static machine behavior in Unity 3D. This script activates one specific behavioral animation, prepared in a web of animation data, when an event starts. The grid system in Unity 3D also controls the locational values of agents on the grid-cells that represent body-to-body competitive behavior and queuing behavior. While SafeBIM enables the representation and observation of such dynamic path-findings, locomotion, and body-to-body behaviors of agents, collaborative behaviors are not inherently equipped, so social dynamics such as yielding or helping cannot be represented.

4.2 SafeBIM

As a way to support convenient use of the simulation method, the present study added the 3D simulation engine SafeBIM to a commercial BIM platform. SafeBIM was developed using Unity 3D, a popular 3D game engine, as its basis and added to Autodesk Revit 2013 (Fig.3.), so the students could use SafeBIM in the Revit toolkit. As a first step of execution, SafeBIM computed the location and dimensional properties of the BIM objects (walls, exit doors) and generated a grid-based collision map for VUsers' wayfinding. Second, students entered the physical characteristics (genders, heights) and numbers of VUsers either randomly or manually, and then populated the VUsers into a collision-computed BIM model. The students also assigned the locations and number of exit doors. Finally, when students executed the simulation, the VUsers evacuated to the exit door nearest their location (Fig.4.).

SafeBIM is based on the A* algorithm, a grid-based shortest-path-finding algorithm and bottom-up interaction between heterogeneous VUsers. The algorithm enables variations in generating the shortest paths so that multi-directional crowds can be represented. These paths are recalculated according to agents' occupancy of grid-cells; this dynamic re-setup of paths initiates the steering behavior of agents. The locomotion and interactive behaviors of an individual agent can be also represented due to the static machine behavior in Unity 3D. This script activates one specific behavioral animation, prepared in a web of animation data, when an event starts. The grid system in Unity 3D also controls the locational values of agents on the grid-cells that represent body-to-body competitive behavior and queuing behavior. While SafeBIM enables the representation and observation of such dynamic path-findings, locomotion, and body-to-body behaviors of agents, collaborative behaviors are not inherently equipped, so social dynamics such as yielding or helping cannot be represented.

5. Results

5.1 Statistical Analysis

Using SPSS 20.0.0 for the analysis, a paired samples T-test was conducted to compare students' self-evaluation scores on how many unexpected problems they discovered in proposed layouts that aimed to support occupants' fast and safe evacuation both with and without the simulation. The results indicate statistically significant scores for using human behavior...
simulation, as the students discovered more unexpected problems in the use of the simulation tool (M = 3.94, SD = 1.03) than when the tool was not employed (M = 3.65, SD = 1.08); t(70) = -2.516, p < .05.

The paired samples T-test was also applied to compare scores on how much confidence the students had in evaluating the usability and validity of the fire exits and evacuee routes in the proposed floor plan, with and without simulation. Analysis of the results indicated that students were more confident in evaluating the usability and validity of the fire egress planning when using the human behavior simulation (M = 4.65, SD = 0.93) than when they did not use the tool (M = 4.20, SD = 0.82): t(70) = -3.480, p < .01.

In the comparison of the efficiency in conducting and experimenting with the processes of fire egress planning, the T-test results indicated that students conducted and experimented with the matches between alternative solutions and evacuees' performances in the processes of fire egress planning more efficiently with the simulation tool (M = 4.47, SD = 0.73) than without the simulation tool (M = 3.88, SD = 0.67): t(70) = -5.129, p < .01.

In the comparison of scores regarding how easily the students determined the design results of fire egress planning, statistical analysis of the results indicated that when students used the human behavior simulation, they determined those solutions more easily (M = 4.51, SD = 0.82) than when they did not use the tool (M = 3.85, SD = 0.87): t(70) = -5.548, p < .01. Table 2. presents the results of statistical analyses in detail.

5.2 Discussion
To interpret the reasons for these results, this study also obtained the students' responses to a question asking what kinds of problems they found most often using human behavior simulation. Fifty-four of 70 students answered that they found expected problems, while 38 listed the unexpected problems. Fifteen of these 54 answered that they discovered that the locations of exits caused inefficient and distant routes of egress, making for inappropriate evacuation performance. Ten of 54 answered that the number of exits caused complicated evacuation routes and bottlenecks, while 8 of 54 found problems with the widths and lengths of corridors and rooms, and 5 students reported that the shape and holistic composition of floor plan layouts were unsuitable for evacuation. Using human behavior simulation thus supports students' problem finding in fire egress planning, specifically with regard to the number and locations of exits, the dimensions of corridor and rooms, and the physical layout of floor plans. In an extension of previous studies, these results can be attributed to the fact that explicit and observational representation of evacuees supports students' problem finding in fire egress planning. In Ekholm's (2001) theoretical framework, analyzing users' activity in design solutions, which is a process of problem finding,
allows for defining and redefining spatial functions and building programs. He argued that representing users' activity facilitates such problem definition and analysis for architects, and thus may promote the functionality and versatility of buildings in accommodating different behaviors among occupants. Hong et al. (2016) reported that observing social behaviors of VUsers enables students to discover the functional problems of design solutions such as accessibility, travel routes, density, and dimensional appropriateness early in the process, thus facilitating iterating design goals and solutions. In both studies, SafeBIM also explicitly visualized body-to-body bottlenecks, evacuation times, distances, and routes of evacuees; this observable representation may help students to discover unexpected floor plan problems in terms of fast and safe fire egress (Fig. 5).

The present study also offers possible causes for the results of the analysis of human behavior simulation’s efficiency in conducting and experimenting with the processes of fire egress planning. Students were also able to manipulate the parameters of VUsers explicitly, so that setting up experimentation variables like the population, locations, and physical characteristics of evacuees became objective and observable to examine evacuees’ performance in the given physical layout. From a technical perspective, SafeBIM provided visual interfaces to manipulate the parameters of VUsers without using additional scripts. In the previous study, Hong et al. (2016) noted that in the use of human behavior simulation, the scripting workloads obstructed students’ fluent experimentation and iterations. In the present study, such workloads were lessened; thus, this easy setup of the parameters of VUsers was interpreted as another reason for the results. The other reason stems from the technical element that SafeBIM, a human behavior simulation platform developed for this study, was integrated into a commercial BIM toolkit, and that the students thus used BIM models directly in order to analyze and evaluate the performances of VUsers’ evacuation without having to employ complex processes to convert the models. As a result, conducting an experimental cycle for solution synthesis, analysis, and evaluation became time-efficient. In Wang et al.’s study (2015), the BIM model was also used for fire safety management, and the authors reported the advantages of an evacuation analysis system integrated with BIM; the 3D geometric visualization of the BIM model was effective and accurate in examining evacuation times, routes, and locations of maintenance equipment. Finally, the present study assesses the reasons why students felt determining fire egress planning solutions was easier and why they had confidence in evaluating the usability and validity of the fire exits and evacuee routes when using the simulation tool. The students reported that explicit, analytic representation helped their decision making in elements like evacuee travel routes, times, and distances, so they believed that evidence-based decisions were more reliable in satisfying the requirements of fire exits than even reasonably well-informed assumptions. While a few students pointed out that the pathfinding performances of VUsers should be improved as much as possible so as to correspond to real-world evacuee routes, most students agreed that simulated evidence enabled them to confirm the ways in which the design solutions were useful and valid in supporting occupants’ fast and safe evacuation.

6. Conclusion

This study has examined the applicability of human behavior simulation for architecture major students’ fire egress planning and discovered that the simulation method helps find and analyze unexpected problems and evaluate the usability and validity of design solutions in fire egress planning. This study also confirms that human behavior simulation enables students to conduct the processes of experimentation more efficiently and determine solutions more easily. Using previous research as a foundation, the present study posits that its findings are rooted in the explicit, analytic, and observable representation of evacuees, their manipulative parameters, and an integrated BIM system that supports the cycles of synthesis, analysis, and evaluation. The limitations of the present study, along with suggestions for future research, are as follows. First, the SafeBIM behavioral model was based on the A* algorithm, which is a cellular automata model. Hence, the physical interactions of evacuees, such as body-to-body competitive behavior and queuing behavior, were computed and represented (Pan et al., 2006; Pelechano & MALKawi, 2008), but social behaviors like yielding were not considered. This lack of social interactions among VUsers may be one reason why a few students questioned the reliability of the simulated results. A future study should include social parameters of evacuees like group affiliation and intimacy that are observed in reality (Chu et al., 2014a). A future study should also adopt recent advances in the perceptual model of evacuees, such as wayfinding according to familiarity with building elements, following visual exit cues and crowd behaviors that resemble actual social facilitation (Chu et al., 2014b). In addition, future studies should investigate the correspondence between the behaviors of actual human users and VUsers in order to improve the reliability of simulated results. Adopting direct-experience simulation is a proven method of collecting the behaviors of actual human evacuees (Sun & de Vries, 2013).

Despite these limitations, the present study reveals the effectiveness and applicability of human behavior simulation for students’ problem finding, decision making, and analyzing and evaluating empirical fire egress planning, proving the hypothetical assumptions of previous simulation studies. The findings of this
study should contribute to improving the current lack of a systemic, rational educational method in fire egress planning and help establish the optimal avenues for developing human behavior simulation platforms.

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