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Effects of Human Behavior Simulation on Usability Factors of Social Sustainability in Architectural Design Education

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Received: 30 June 2020; Accepted: 20 August 2020; Published: 31 August 2020

Abstract: While the social sustainability of built environments is an essential aspect of architectural design education, systemic experiments still lack empirical pedagogy. Therefore, factors of social sustainability are hardly reflected in students' projects seamlessly. To overcome such limitations, this study investigates the applicability and effectiveness of human behavior simulation. To ensure authentic architectural design, the projects were equipped with autonomous, rational anthropomorphic computer agents called virtual users (VUsers). This study compared the performance scores on social sustainability factors, assessed by the students who conducted design projects both before (without) and after (with) using the simulation. A one-way analysis of variance indicated that human behavior simulation promoted the performance of projects with respect to the parameters of accessibility and safety, ergonomic usability for heterogeneous users and supportability of social interactions. However, the simulation was not found to be effective in promoting the physical attractiveness of built environments and in ensuring the completeness of design solutions. Based on previous studies, the present study interpreted the reasons why the operability of VUsers and built environments, representations of emerging interactions of VUsers and whole-and-part analytics promoted explicit experimentation, but the factors of physical attractiveness and completeness were irrelevant to the rational examinations in the use of the simulation.

Keywords: human behavior simulation; virtual users; social sustainability; performance analysis; evaluation method; architectural design education

1. Introduction

A contemporary definition of sustainability does not rest on merely environmental and ecological performance. Instead, it extends to include the impacts on the sociopsychological behaviors of occupants who use a built environment [1–3]. A built environment that is satisfactory and safe for members of society guarantees durability and usability and thus reduces the frequency of construction and demolition [1,4]. The occupants' emotional bonds with a built environment also inspire active, participatory maintenance, and such emotional bonds emerge from vibrant social interactions among the occupants [1,5]. The concept of social sustainability includes the maintenance, improvement and well-being of current and future generations [4]. Therefore, training on the design strategies for achieving such socially sustainable built environments is one of the most significant aims in the field of architectural design education [6,7].

Previous studies stated that the behavioral traits of occupants in built environments, such as accessibility, safety and psychological needs, are the key success factors for social sustainability [1,4,5,8].

However, in empirical design education, few systematic experiments related to these factors have been conducted due to the lack of a valid method for analysis and evaluation [1,5,8]. The investigation of the occupants' behaviors on social sustainability relies merely on the extrapolations from partial rules and similar previous cases [9]. Thus, if designers attempt to examine the relationship between physical architecture and social sustainability, inherent gaps are observed when the designed solution is beyond the range of extrapolations [7,10].

To overcome the methodological shortcomings, research endeavors in the field of design computation have proposed several simulation methods [11]. In the simulation methods, the environmental and engineering factors are well-formulized, and the relevant performances, such as energy simulations, can be computed. However, it is still difficult to analyze the factors influencing social sustainability [9]. The agent-based simulation method developed recently allows for computation of autonomous, interpersonal behavior of human occupants, called human behavior simulation [10,12,13]. This simulation method involves AI-equipped virtual users who respond to environmental and social stimuli. The behavior of the virtual users is tailored to fulfill the given sociopsychological needs and preferences. Thus, socially sustainable performance in built environments, such as on accessibility and safety, can be analyzed. Unlike in other types of agent-based simulations, such behaviors of the virtual users are a result of the bottom-up interactions among them. Responsive interactions can also be observed and analyzed [13–15].

Though previous studies adopted the simulation method to assess fire egress performance and students' design inspirations [16–19], the enablers of and barriers to human behavior simulation in socially sustainable architectural design experiments are still unknown. In particular, from an educational perspective, several previous studies explored the effects of the simulation method in iterating students' authentic design projects, but systematic investigations and statistical analyses were not conducted [14]. Therefore, this study aims to investigate the empirical, explicit effects of human behavior simulation on students' design experiments that focus on hypothetical performance between the public facilities and occupants' behaviors as the factors of social sustainability. This study also evaluates the applicability of the pioneering and unique simulation method in resolving the urgent need for systematic analysis and evaluation of social sustainability.

2. Literature Review

2.1. Social Sustainability in Architectural Design Education

Previous sustainability studies agree that sustainability is a combination of environmental, social and economic components [1,5]. Social sustainability highlights social equity, or the lack thereof, in the usage of a built environment [1,5,8]. Accessibility, a common aspect of social sustainability, addresses issues related to convenient access to certain places in the occupants' daily lives or adverse circumstances, regardless of their physiological and social vulnerability [5,20,21]. Accessibility also promotes public participation, which triggers emotional attachment to the place where the occupants belong [1]. The previous frameworks on social sustainability also stated that well-being, safety, security and accessibility encourage active participation and social interactions. Social interactions develop a sense of belonging and social cohesion [22,23]. Acceptable levels of functionality and comfort are key factors for a sustainable community, which also impacts the occupants' behavioral and sociopsychological needs and, ultimately, their quality of life [1,5].

Chan and Lee [8] categorized the measurable aspects of social sustainability. Based on the occupants' behaviors, the authors listed (1) access to public facilities; (2) convenience, efficiency and safety for pedestrians and public transport users to promote user satisfaction; (3) management of the building, facilities and spaces related to the conservation of resources and the surroundings; (4) access to work; (5) proximity to business activities in order to fulfill daily life operations; and (6) access to open space. The authors also emphasized the appearance, density, height, quality and mass of buildings and availability of open spaces, all of which can help citizens maintain the conditions of the built environment, prevent premature deterioration and minimize repair costs. Eizenberg and Jabareen [2] also defined similar factors influencing the social sustainability of built environments. In addition, Atanda [5] emphasized developing a performance assessment tool that can facilitate users' quality of life within a built environment based on social sustainability indicators such as equity, environmental awareness and sensibility, social interactions, ease of accessibility and satisfaction.

In the field of architectural design education, the importance of social sustainability has been emphasized, but the methodologies that enable students to examine and explore performance on social sustainability are rarely introduced in empirical design education [9]. Rieh et al. [7] pointed out that a balanced, well-organized curriculum, which integrates the theories and principles of sustainability into design courses, enhanced students' ability to produce high-quality sustainable design solutions. The authors emphasized the empirical applicability of knowledge learned in theory courses in design studios through complementary allocations between the two types of courses. Macroeducational systems, such as architectural accrediting, should allow for such strategic integration into the curriculum. The authors also stated that current design pedagogy fails to inculcate a holistic amalgamation of environmental, sociocultural and economic factors of sustainability.

From the perspective of design methodology, such barriers occur due to not only the rigidity of educational standards but also the lack of experimental methods that enable and motivate students to conduct learning by doing in search of an optimal solution. Ultimately, sustainability-centric architectural education aims to nurture future experts to orchestrate heterogeneous factors of sustainability and other factors. To examine such trade-offs, as Rittel [24] emphasized, students need to learn ways in which design configuration matches the contextual performance. Inductive experimentation, for instance, enables students to discover unknown facts and provides opportunities to rethink conventional views on sustainability beyond precedent case-based extrapolation methods.

Despite such advantages, experimentation methods are hard to use in empirical design pedagogy because of constraints related to costs, physical space, time and other resources for valid installation. Social sustainability is limited to conducting systematic experimentation. To evaluate the social equity and accessibility of design solutions, the physiological and sociopsychological parameters of occupants should be examined and applied to ongoing design developments. The physical properties of the built environment should be matched with the behaviors of occupants using explicit and analytical information. However, the heterogeneous, diverse and complex parameters of occupants corresponding to a full-scale built environment are hard to iterate in experimental settings.

Existing knowledge, largely about previous rules and case studies, is used to develop social-sustainability-centric design solutions. In the empirical fields of design education, students used to adopt conventional matches between social sustainability factors and physical elements of design. On the other hand, they would also develop not yet fully matured, abstract design solutions, which were closer to expectations than actual performance, in which the nature of design problems was inherently unique. The lack of experimentation methods obstructs fluent search and trade-offs in the search for optimal parameters to fulfill the occupants' desires and social sustainability. Hence, valid measurements and analyses are rarely stated in empirical design pedagogy.

Compared to the social sustainability factors, environmental and ecological sustainability factors are investigated by experimental methods, such as full-scale mock-ups, full-scale actuals and computer simulations [11]. Computer simulation, in particular, is regarded as one of the prominent means to overcome the lack of experimental methods for evaluating social sustainability. The next section explains the hypothetical relationships in which human behavior simulation can facilitate students' experimentation on authentic social-sustainability-centric design projects.

2.2. Hypothetical Relationship between Human Behavior Simulation and Social Sustainability

Human behavior simulation is enabled by autonomous, AI-equipped computer agents called virtual users (VUsers) [10,12]. These VUsers compute observable as well as analytical behavioral responsiveness to the given built environment. We can also observe their physiological and psychological parameters, while the behavioral rules are preprogrammed and customized by the operators. These technological capabilities enable systemic experiments that iterate the ways in which physical configurations and elements of the built environment influence the occupants in specific contexts and represent the actual behavior of the occupants of the built environment. They can also help measure accessibility, introduce emerging social interactions, ensure comfort and safety of the occupants, etc. (Figure 1).

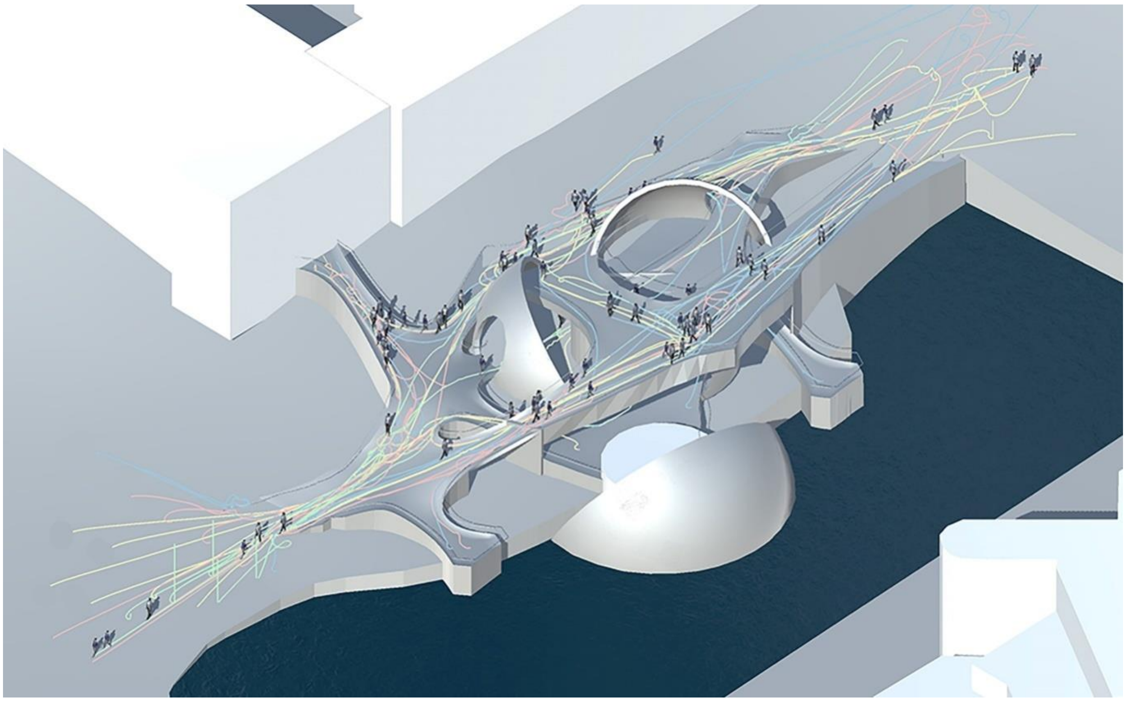


Figure 1. An example of a human behavior simulation. In a community center project, students analyzed accessibility and interpersonal interactions through the use of human behavior simulation [25].

Hong et al. [14] investigated the applicability of human behavior simulation in the empirical design studio. They analyzed how students have iterated and reframed design aims and solutions to develop four authentic architectural design projects. They observed that behavioral simulation helped in analyzing the functionality of design configurations (zone, dimensional appropriateness, etc.) and the psychological and social implications of design solutions (gender-related responsiveness, privacy, intimacy, coziness, etc.). According to the study, the students initially observed bottom-up behaviors of VUsers responding to small-scale prototypes. When the students developed the prototypes of master plans, they analyzed holistic functionality (e.g., circulation, bottlenecks) and iterated VUser variables to develop a design that enhanced the performance of a final solution. The authors pointed out that the unexpected behavior of VUsers facilitated simulation-aided design development.

Human behavior simulation was also applied for the resolution of students' problems in design development [17] and fire egress planning [26]. These studies reported that the analytical and observable representation of human behavior and the manipulability of the parameters of the users' impact on fluent experiments enhanced the functionality of design solutions. Barring these pioneering studies, most human behavior simulation studies primarily focused on technical developments of behavioral models and simulation platforms [16,18,19,27]. The previous studies also attempted to apply the simulation for analyzing the functional performance of buildings such as hospitals and offices, which were essentially the students' design experiments related to social sustainability [13,15,28].

From the pedagogical perspective of social sustainability, this study deduces that human behavior simulation is a potentially salient method for resolving the shortcomings of experimental methodologies in empirical design education. Human behavior simulation can allow students to iterate the parameters of built environments and the heterogeneity of occupants, such as physiological parameters (e.g., height, gender, age, physical durability, etc.), psychological parameters (e.g., emotional bonds, interest, coziness, etc.) and behavioral rules (e.g., encounter, avoid, yield, help, etc.). Therefore, students can conduct experiments fluently to search for ways in which design configurations support the main, consensual factors of social sustainability (such as equity of access, safety, usability for heterogeneous users, social interactions, further architectural attractiveness and design quality). Analytical representations and emerging, bottom-up interactions of VUsers can also help students analyze and evaluate users' behaviors, respond to novel prototypes of the design and enhance the holistic completeness of design solutions. While this theoretical deduction indicates that human behavior simulation is effective for supporting social-sustainability-centric design education, its effectiveness is not yet established.

Therefore, this study aims to investigate the effectiveness of human behavior simulation on students' experimentation and self-learning performance related to usability factors of social-sustainability-centric architectural design (accessibility and safety, ergonomic usability, social interactions and physical attractiveness) and a factor of design development (completeness). To examine the goals, this study adopted statistical comparisons between the experimentation and self-learning outcomes before using (without) the simulation and after using (with) the simulation. The students' self-evaluations on each output indicate educational effects implicitly: how much the students experimented and learned the usability performance of their architectural design projects within the scope of social sustainability and how much they developed this quality. Based on the research aims, this study framed the following alternative hypotheses:

Hypothesis 1 (H1). *In students' experimentation and learning outcomes, human behavior simulation better promotes the occupants' accessibility and safety than its absence does.*

Hypothesis 2 (H2). *In students' experimentation and learning outcomes, human behavior simulation better promotes ergonomic usability to support heterogeneous users than its absence does.*

Hypothesis 3 (H3). *In students' experimentation and learning outcomes, human behavior simulation better promotes social interactions than its absence does.*

Hypothesis 4 (H4). *In students' experimentation and learning outcomes, human behavior simulation better improves the physical attractiveness of the built environment than its absence does.*

Hypothesis 5 (H5). *In students' experimentation and learning outcomes, human behavior simulation better promotes the completeness of the design than its absence does.*

3. Materials and Methodology

3.1. Participants

The study collected data from an authentic design course held at Inha University, South Korea. From 2017 to 2018, 42 students enrolled in the course, of which 25 (59.5%) were male and 17 (40.5%) were female. Their ages ranged from 22 to 26, and the average age was 23.57. During a full semester, they designed and developed 16 projects related to social facilities and public architecture that corresponded to the concepts of social sustainability. Figure 2 depicts some of these projects, such as urban and natural parks, various types of bridges, observatories, waterfronts and seaside facilities.

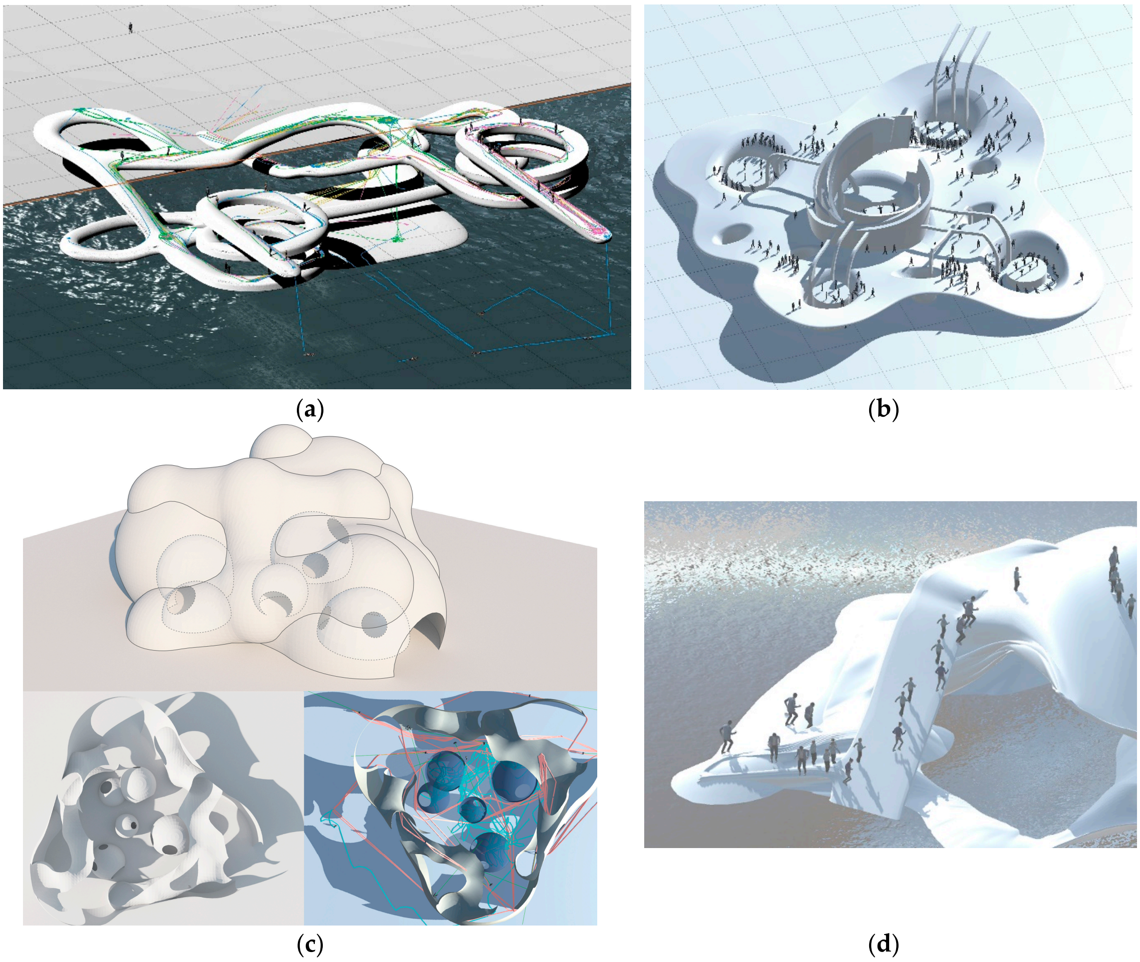
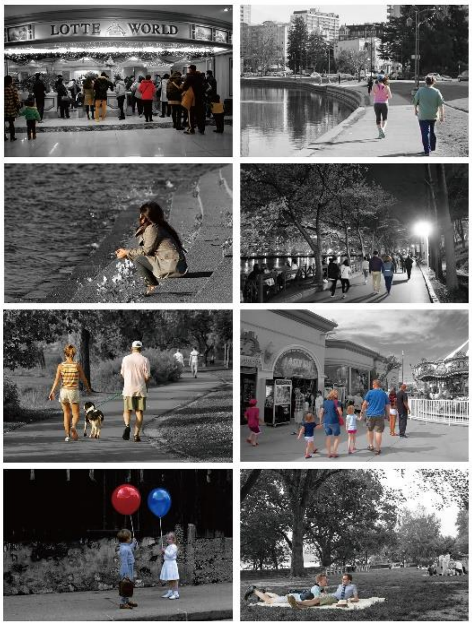


Figure 2. Examples of social facilities and public architecture design projects ((**a**) [29], (**b**) [30], (**c**) [31], (**d**) [32]).

3.2. Procedure

The students proposed hypotheses to find ways in which heterogeneous occupants would respond to the desired design configurations and to arrive at an optimal design that would minimize behavioral conflicts and risk amongst them and thus promote social sustainability. To conduct these experiments, the students observed behavioral patterns of the users and specified the various physiological and psychological parameters of heterogeneous users. At this step, the students listed occupant types and their responsive behaviors in real and existing built environments that were similar to the purposes, scales and sites of the intended design solutions. The data collection was conducted by direct field observation and surveys, and the students sorted the data as the criteria of personal traits, observable behaviors and environmental and social stimuli that triggered behavioral responsiveness (Figure 3). To collect such data and detect phenomena in real built environments, the students used cameras and hand-drawn sketches. The students also collected unique cultural and social behaviors (e.g., bowing, yielding to elders) in order to reflect the parameters of VUsers. After the data collection and survey step, the students prescribed the hypothesized performance metrics of the design solutions, such as circulation distance and time and frequency and location of bottlenecks and collisions, that indicated accessibility and safety.



	Sex	Behavior	Age	Height
1	Male	Walking elderly couple (M)	68	168cm
2	Female	Walking elderly couple (W)	65	157cm
3	Male	Walking with a dog	34	174cm
4	Male	Couple on a picnic (M)	24	182cm
5	Female	Couple on a picnic (W)	22	168cm
6	Male	Baby playing around the playground	3	90cm
7	Female	Child carrying a balloon	6	110cm
8	Male	Exercising	42	177cm
9	Male	Grandfather who went shopping	62	172cm
10	Female	Granddaughter who went shopping	8	128cm
11	Male	Riding a bike around the park	25	174cm
12	Male	Sitting on the park chairs drinking coffee	37	175cm

Figure 3. An example of a behavior survey and data collection [33].

To perform comparative investigations, the students evaluated the performance of design prototypes before using the simulation method. They based their results on previous case studies, personal experience and assumptions to develop design solutions. Subsequently, the students simulated users' behaviors in the design prototypes and found ways in which the simulation supported or obstructed their design experiments.

During the course, the students also learned to use Unity 3D, a commercial 3D simulation platform, to implement the human behavior simulation empirically. They modeled the design prototypes and solutions for social facilities and the physiological shape and motion data of VUsers. Based on these, they programmed the psychological parameters of VUsers and formulated behavioral rules using C#. At this scripting step, the students defined the listed traits of occupants as Boolean variables that had a true or false value, and they coded independent behavioral states of occupants' behaviors, such as "walk", "run", "play" and "watch". The finite-state machine algorithm indicated that behavioral states transited from one to another via transition links, and only one behavioral state was activated at a time (Figure 4). Conditional statements were also coded to activate such behavioral transitions. For instance, if a VUser preferred to play adjacent to water, and at the same time, if the VUser also watched a designed waterside, the behavioral state of the VUser transited from "walk" to "play" (Figure 5). Microsoft Visual Studio 2017 was used to code and edit the C# scripts.

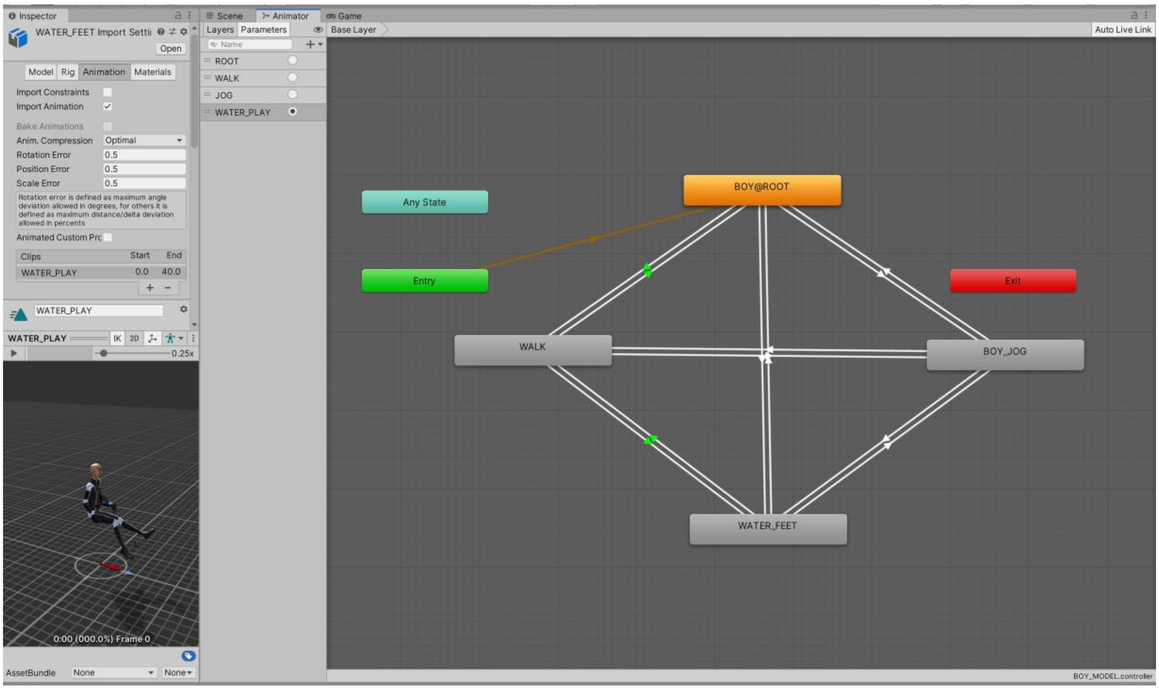


Figure 4. An example of the finite-state machine in Unity 3D [33].

```
void Update ()
{

        if (preferWater == true && seeWater == true) {

            if (play == true) {

                playWait += Time.deltaTime;

                if (playWait > playWaitTime) {

                    Walk ();

                }

            } else {

                    Play ();
            }

        }

    }
```

```
void Walk()
{

    dist = Vector3.Distance (vuserTr.position, target[targetIndex].position);
        vuser.destination = target[targetIndex].position;
        ani.SetTrigger ("WALK");

    }


void Play()
{

        ani.SetTrigger ("WATERFEET");
        vuser.destination = vuserTr.position;
        vuser.baseOffset = -0.5f;
        play = true;
}
```

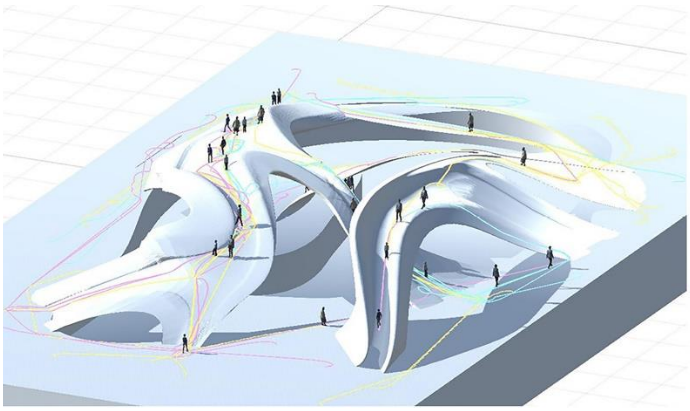
Figure 5. An example of behavior transition codes in C# [33].

The students also experimented on the design performance in the two contexts—one was ordinary, and the other was an eventual situation. Compared to the ordinary situation, social events (e.g., street festivals, social meetings, emergencies, etc.) affected density, occupancy rates, population amounts and circulation patterns of VUsers. In coding, the students installed each ordinary and eventual situation as Boolean variables. Once an eventual situation turned on, VUsers transited between behavioral states and moved to particular VUsers or destinations, as explained in the finite-state machine algorithm. For instance, if a festival event happened, any VUsers who preferred to watch fireworks transited their behavioral state from "walk" to "watch". To watch the fireworks, the VUsers also moved to the given destinations (Figures 6 and 7).

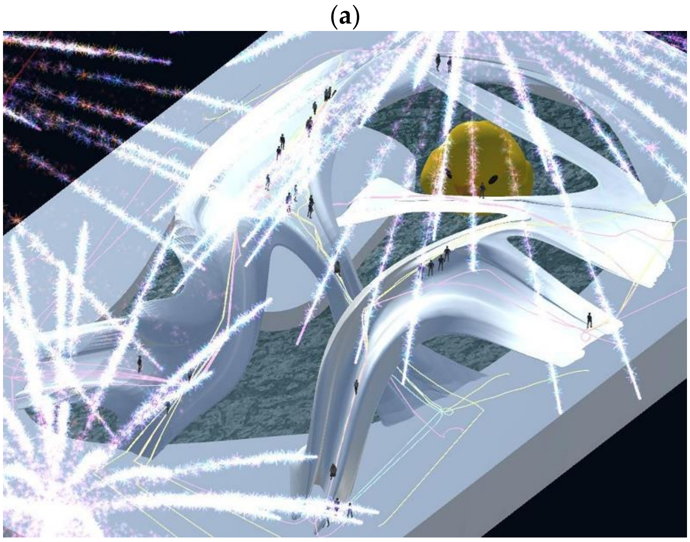
```
void Update()
{
    if (preferFirework == true)
    {
        Watch_Firework();
    }
    else if (preferDuck == true)
    {
        Watch_Duck();
    }
    else if (preferFirework == false || preferDuck == false)
    {
        if (preferWater == true && seeWater == true)
        {
            if (play == true)
            {
                Walk();
            }
        }
        else
        {
            Play();
        }
    }
}
```

```
void Walk()
{
    dist = Vector3.Distance (vuserTr.position, target[targetIndex].position);

      vuser.destination = target[targetIndex].position;
       ani.SetTrigger ("WALK");
       walkingDistance++;
}

void Watch_Firework()
{
    ani.SetTrigger ("WATCH_FIREWORK");
    vuser.destination = vuserTr.position;
    vuser.baseOffset = 0.0f;
    seeF = true;
}
```

Figure 6. An example of behavior transition codes in events [33].



(**a**)



(**b**)

Figure 7. Final solution simulation in an eventual situation ((**a**) circulation in ordinary situation, (**b**) circulation in fireworks) [33].

The social facility and public architectural design projects required explicit analysis and evaluation of the satisfaction and conflicts among the users in response to physical forms and zoning of built environments. As a factor of social sustainability, the attractiveness of design configurations was also evaluated [1,5,8].

As an example, in a park bridge project titled Festival Bridge, the students surveyed four types of prospective users. The users had different shapes, heights and physical capacities (walking speeds and perceptions). They also had incongruent opinions and behaviors regarding design configurations of the bridge. For instance, while elders preferred to stroll on the bridge in safety, children preferred to dabble on the adjacent waterside. The adults also wanted to walk on the bridge as couples or small groups. The students manipulated the vertical and horizontal parameters of the bridge's curvature and evaluated how well the parameters of the bridge satisfied the varying and conflicting behaviors of the users. In the simulation, the students analyzed walking distances and duration and the frequency and location of collisions, bottlenecks and social interactions in the three design prototypes (Figure 8). Based on the explicit analyses, they examined and obtained an optimal match between the design prototypes based on physical attractiveness and social sustainability parameters such as accessibility and safety, ergonomic usability and supportability of social interactions. The students also developed one prototype to enhance the performance in both ordinary and eventual situations when the users' population and behavioral rules varied according to social and visual stimuli—for instance, fireworks adjacent to the bridge (Figure 7).

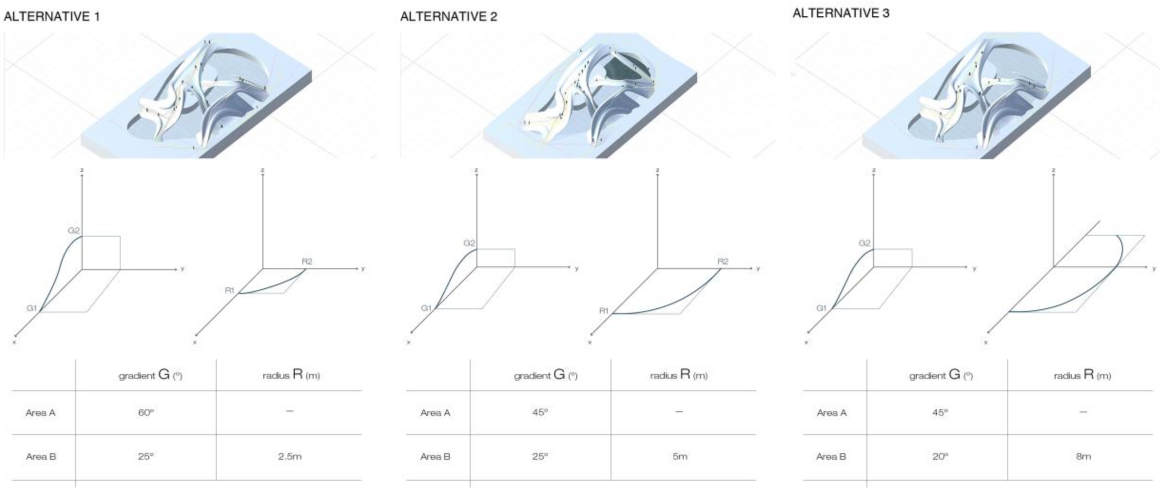
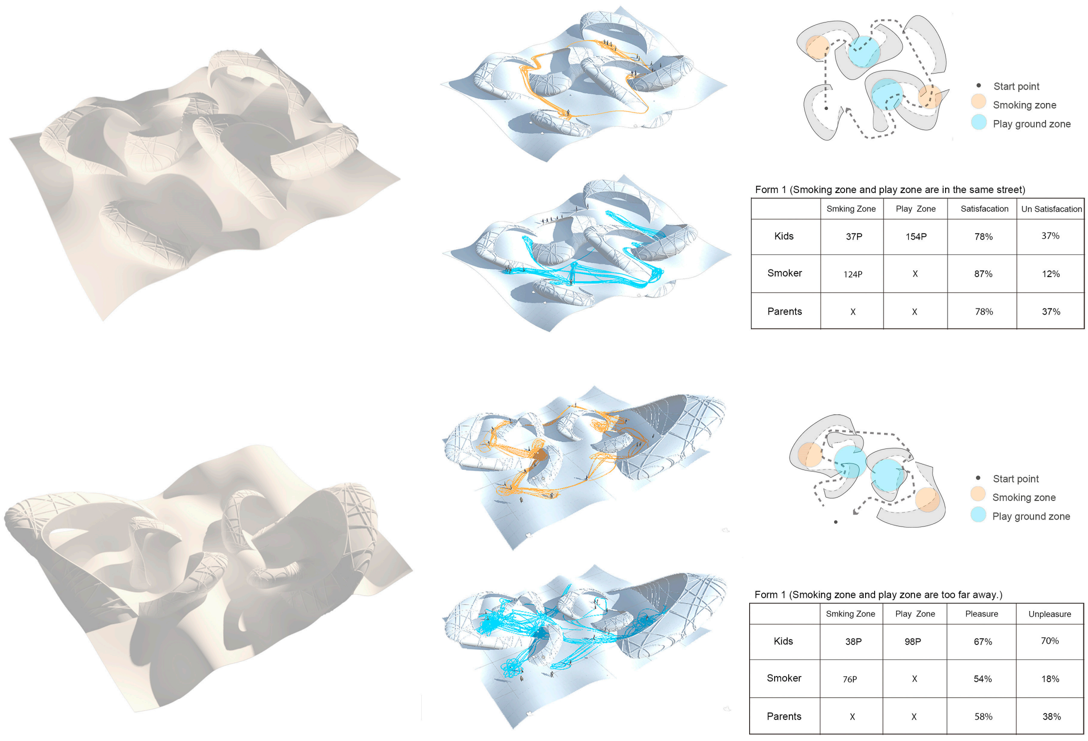


Figure 8. Prototype simulation [33].

In another example, in a public park project titled Smoking vs. Nonsmoking, the students iterated design configurations (heights, widths and forms) and locations for smoking and children's playground zones and examined design prototypes to satisfy three types of users who exhibited conflicting behaviors. Among the users, while children preferred to access playgrounds in the park but avoid smoking zones, smokers tended to access smoking zones quickly and did not invite the children who intruded into the smoking zones. Parents needed to pay attention to their children and needed quick access to them. Through human behavior simulation, the students evaluated the walking distances and duration for all types of users. They measured the frequency, locations and duration of the children's exposure to smoke, visual connectivity of the parents and the children and occupation capacities of the playgrounds and smoking zones (Figure 9). In such experiments, the students developed a balanced solution that satisfied the needs of heterogeneous users, attempting to promote sustainable occupancy of the designed park.



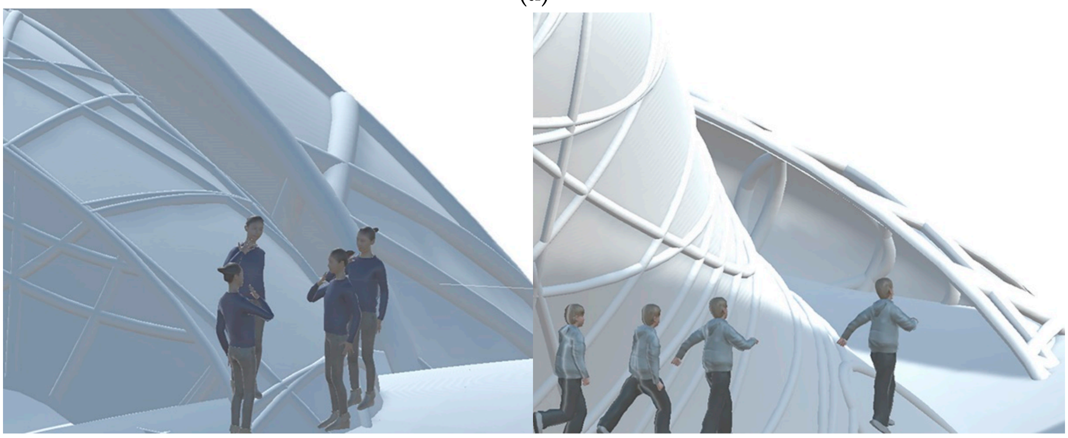
Form 1 (Smoking zone and play zone are in the same street)

	Smking Zone	Play Zone	Satisfacation	Un Satisfacation
Kids	37P	154P	78%	37%
Smoker	124P	X	87%	12%
Parents	X	X	78%	37%

Form 1 (Smoking zone and play zone are too far away.)

	Smking Zone	Play Zone	Pleasure	Unpleasure
Kids	38P	98P	67%	70%
Smoker	76P	X	54%	18%
Parents	X	X	58%	38%

(**a**)



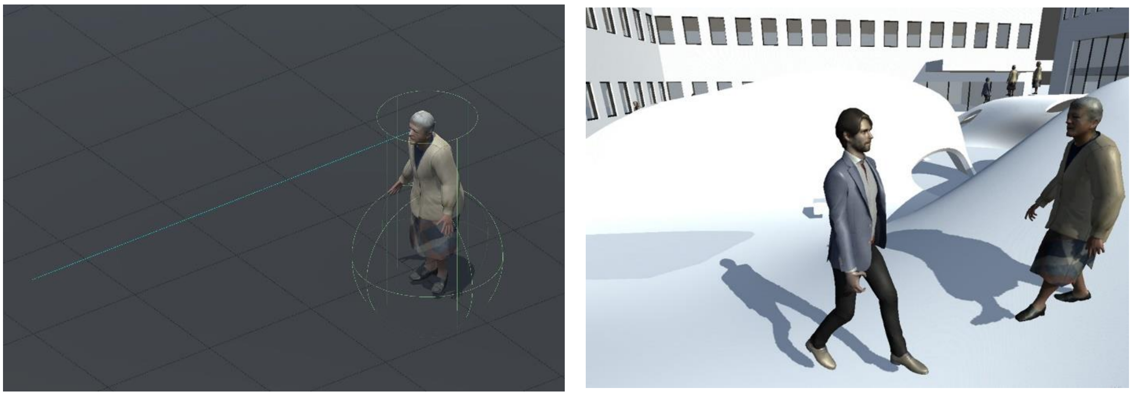
(**b**)

Figure 9. Final solution simulation in an eventual situation ((**a**) behavior analysis between smoking and nonsmoking zones, (**b**) behavior conflict between smokers and nonsmokers) [34].

3.3. Parameters of VUsers

In all sixteen projects, VUsers were equipped with physiological traits, psychological needs, pathfinding parameters, visual perception and behavioral rules. Relying on previously conducted surveys, the students modeled and animated the physical shapes and motions of VUsers. These physiological data were created in Autodesk 3ds Max and integrated into Unity 3D. The heuristic A* algorithm was also used for the pathfinding of VUsers. The A* algorithm, adopted in Unity 3D, computed the shortest paths taken by the VUsers on the grids and explained the complex geometries (e.g., curvature, multistory buildings) and changes in locations of obstacles efficiently. The algorithm also provided the avoidance and yielding parameters among the VUsers, which the students applied to examine the social dynamics among the VUsers. The students also installed a visual capability for the VUsers by computing physical collisions between line-shaped rays and objects. The students also coded and modified behavioral rules for the VUsers based on the objectives of the simulations. The VUsers switched between the preprogrammed behavioral branches based on the finite-state machine algorithm, explained in the previous Procedure section, and responded to physical objects, invisible zones and events. The course instructor consulted and helped with the technical implementation.

For instance, to analyze the suitability of a public park adjacent to an eldercare facility, the students animated and coded walking motions, gestures and abilities of the elderly VUsers and installed physical rays to compute the visual capacity of the elders. When the vision rays collided with objects or people of interest, the elderly VUsers switched their ongoing behavior and attempted to access them. This mechanism simulated a way to emulate the behavior of elders who have Alzheimer's disease (Figure 10).



(**a**) (**b**)

Figure 10. An example of virtual user (VUser) parameters: the elderly VUser was equipped with a vision ray and motions (**a**). If the vision ray touched people of interest, the VUser transited her destination from an initial point to the detected man-shaped VUser (**b**). If the man was out of the vision ray of the elder, as a result, she lost her way, as Alzheimer's patients [35].

3.4. Metrics

In this study, the students developed architectural design projects for one semester. As mentioned in the Procedure section, during the first half of the semester, they modeled design solutions and hypothesized and predicted the performance of their projects. The students developed design solutions, deduced from previous cases and experiences, without using human behavior simulation. In the remaining half of the semester, the students examined and developed the design solutions using the simulation. After completing the full semester, the students rated the performance of their design solutions in terms of their ability to support and achieve (1) the occupants' accessibility and safety, (2) ergonomic usability for heterogeneous users, (3) social interactions, (4) physical attractiveness of built environments and (5) completeness of the design for both scenarios, that is, before and after using human behavior simulation (Figure 11). In this study, the safety factor indicated the occupants' fluent circulation status without hazardous collisions and bottlenecks. The survey questions evaluated the students' authentic and empirical experiences in the explicit and direct use of human behavior simulation compared to the case when it was not used. This quasi-comparative method was often used in previous studies that investigated the ecological validity and effectiveness of design methods and tools [17,25,28,36]. In the survey, the Likert scale had seven points (7 = very high, 0 = not at all), and the reliability of the measures was a Cronbach's alpha of 0.73. The collected quantitative data were analyzed using a one-way analysis of variance (ANOVA).

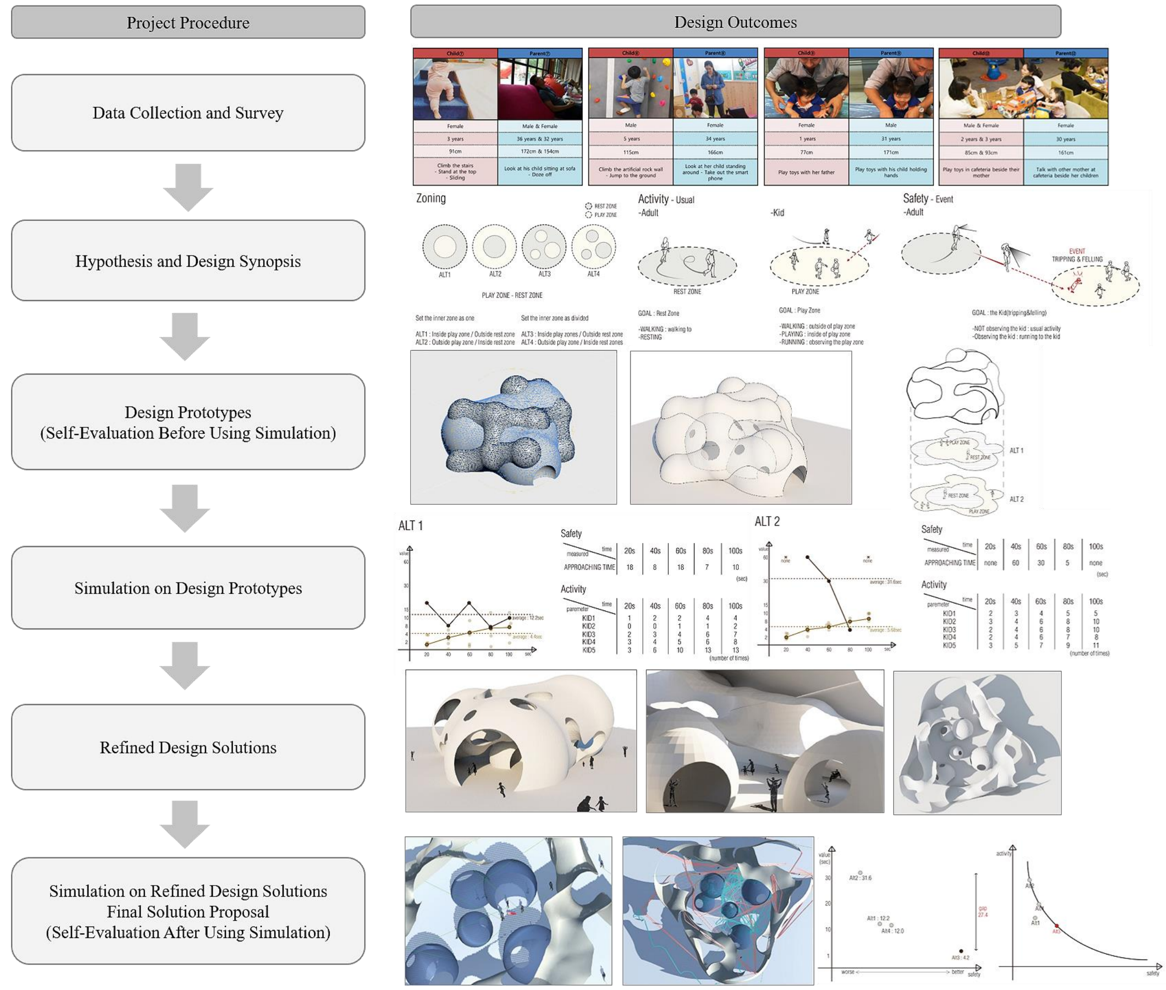


Figure 11. Project procedure and samples of design outcomes [31].

4. Results

ANOVA compared the scores concerning the occupants' accessibility and safety, ergonomic usability, the supportability of social interactions, physical attractiveness of the built environment and completeness of the design both before using (without) and after using (with) human behavior simulation. The results indicated that the scores were significantly different across both scenarios, $F(1, 12.18)$, $p = 0.00$, $F(1, 7.93)$, $p = 0.01$, $F(1, 4.69)$, $p = 0.03$ in sequence (Table 1). The students concluded that human behavior simulation better promoted performance on occupants' accessibility and safety ($M = 5.79$, $SD = 0.81$) compared to not using human behavior simulation ($M = 5.02$, $SD = 1.16$). The ergonomic usability to support heterogeneous users after using simulation was found to be better ($M = 5.55$, $SD = 0.80$) than before using simulation ($M = 4.93$, $SD = 1.18$). Similar patterns were observed for the performance on supportability of social interactions, with human simulation faring better ($M = 5.74$, $SD = 0.99$) than the other case ($M = 5.24$, $SD = 1.12$).

The ANOVA results established that the respective scores for physical attractiveness of the built environment and completeness of the design were not significantly different before and after using human behavior simulation, $F(1, 0.387)$, $p = 0.53$, $F(1, 0.37)$, $p = 0.77$ in sequence (Table 1). The students concluded that with human behavior simulation, the physical attractiveness of the built environment of their design project was not too different ($M = 5.29$, $SD = 0.86$) from when it was not used ($M = 5.43$, $SD = 1.21$). They also assessed that with human behavior simulation, the completeness of their design project was similar in both cases ($M = 5.31$, $SD = 1.11$ and $M = 5.38$, $SD = 1.10$).

Table 1. Comparison of social sustainability factors without and with human behavior simulation.

	M (SD)		Mean Difference	*p*
	Without Simulation (Before Using Simulation) (n = 42)	**With Simulation (After Using Simulation) (n = 42)**		
Occupants' accessibility and safety	5.02 (1.16)	5.79 (0.81)	−0.76	0.00 **
Ergonomic usability	4.93 (1.18)	5.55 (0.80)	−0.62	0.01 **
Supportability of social interactions	5.24 (1.12)	5.74 (0.99)	−0.50	0.03 *
Physical attractiveness of built environment	5.43 (1.21)	5.29 (0.86)	0.14	0.53
Completeness of design	5.38 (1.10)	5.31 (1.11)	0.07	0.77

* $p < 0.05$; ** $p < 0.01$

5. Discussion and Conclusions

The statistical analysis based on the experiments conducted by students indicated that human behavior simulation enhanced the factors affecting social sustainability in authentic architectural design projects. These factors include accessibility and safety, ergonomic usability and social interactions of heterogeneous occupants. The analysis also helped conclude that human behavior simulation usage had no impact on the factors of physical attractiveness and completeness of design solutions.

Based on the findings of previous studies, this study interpreted the statistical results as follows: First, the operability of both the parameters relevant to VUsers and design configurations enabled the students to iterate optimal matches, which enhanced social sustainability. Relative to the interpretation, Hong et al. [14] reported that students initially iterated the parameters of design configuration and observed the responsive behaviors of VUsers according to the changes. Once the students determined an optimal solution, they iterated the parameters of VUsers and contexts to refine the details of the solution that satisfied heterogeneous users.

The explicit representation of emerging bottom-up interactions among VUsers was also a possible explanation for how the simulation enhanced safety, ergonomic usability and social interactions of design solutions. The previous studies [14] stated that unexpected behaviors of VUsers, which are likely to occur in reality, were computed during rational pathfinding. Social dynamics such as collisions, avoidance and yielding were also computable and represented explicitly. Thus, such descriptive behaviors of VUsers allowed the students to further discover potential safety concerns in their design solutions. The frequency and location of interpersonal interactions were also observed. Based on the population (e.g., single, small group, large group, etc.), subtle details of design configurations were examined within the range of the VUsers' bodies (e.g., using narrow slopes and corners), which represented spatial developments [37,38].

Holistic analytics of the simulation was interpreted as one salient reason relevant to the results. Due to the holistic analytics, the students were able to detect a part-whole relationship of their design solutions related to accessibility and safety. Previous studies [15,39,40] reported such an inherent affordance of the simulation. Small changes in design configurations, attractive stimuli, semantics and scheduled tasks of occupants had an impact on the holistic usability of built environments. Because such complex relationships were captured and summarized, the relevant functional problems were addressed.

In direct observation of the students' experimentation and self-learning outputs, compared to initial concepts and early stages of design prototypes before using human behavior simulation, as conveyed in Figure 11, physical shapes (height, width), curvature, scales and layouts of walls and fenestrations were calibrated to support occupants' safe and easy accessibility, which resolved detected bottlenecks and collisions. The details of walls were also sophisticated to satisfy diverse activities of prospective users. To facilitate opportunities for social interactions, the shapes, scales and locations of void zones were also optimized. While the initial design prototypes were either generic or schematic, final solutions after the simulation were customized to suit the behaviors of users. Therefore, this study interpreted that such experimentation and self-learning outcomes relied on the observable, bottom-up interactions and holistic analytics of the simulation.

This study also interpreted why human behavior simulation did not have a salient effect that promoted the factors of physical attractiveness and completeness of the design solutions. Kalay [10] stated that optimum design is a trade-off between design aims and constraints. Thus, the students may have modified and abandoned physical attractiveness to enhance other functionalities, such as accessibility and safety. Another interpretation rests on the nature of aesthetic evaluations of physical attractiveness, which is a qualitative judgment based on the architects' inherent styles and cognitive capacities [10]. Therefore, physical attractiveness could be considered less relevant than a rational analysis of the simulation. Similarly, the completeness of design solutions was influenced by the trade-offs between aesthetic quality and functional performance.

This study also captured the inherent limitations and suggested relevant future studies. This study relied on authentic design projects in empirical education. While such authentic cases satisfy ecological validity, future studies should adopt rigorous lab experiments to validate and confirm the results of this study. Social facilities, which served as the experimental material for this study, are characterized by limitations in sculptural and novel forms. Thus, the projects selected for this study may not necessarily represent the architectural details that influence the score of completeness of design solutions. Therefore, future studies need to utilize building-sized projects to confirm the results of this study. In this study, the factor of safety only included occupants' physical use of the facilities, such as unexpected collisions and bottlenecks. However, the concept of safety also includes crime prevention, and thus, future studies should attempt to include crime prevention simulations [27]. To fluently conduct simulations, future studies should adopt advanced social and collaborative models of VUsers. For instance, Schaumann et al. [15] developed a narrative coordination system that enables efficient management of complex and massive data about the VUsers' interpersonal behaviors by manipulating event parameters. Chu et al. [16] also proposed an autonomous interpersonal model that computes intimacy and social relationships among agents during a fire evacuation. In this study, social stimuli and events triggered rapid changes in occupants' behaviors rather than environmental stimuli, such as weather conditions and seasonal conditions. While the behavioral mechanism of VUsers responding to social events is similar to their responses according to the weather and seasonal conditions, which means VUsers attempt to visit and stay in their favorite and comfortable parts of built environments, the statistical data on weather and seasonal conditions are salient factors to trigger diverse, autonomous behaviors of VUsers. Computational models of weather and seasonal factors (e.g., sunlight, daylight, humidity, temperature and airflows) also can be integrated into a human behavior simulation platform in order to compute comprehensive environmental and social stimuli in built environments. Therefore, future studies need to include the weather and seasonal conditions in a simulation system. Lastly, this study excluded two key components of sustainability: environmental and economic elements [8]. From the perspective of design pedagogy, extended to the study by Rhie et al. [7], future studies should aim to integrate human behavior simulation into environmental and economic simulations and thus attempt to examine an integrated computational system that simulates holistic components of sustainability.

Despite the listed limitations, we can safely conclude that this study discovered and addressed the empirical applicability and effectiveness of human behavior simulation to aid social-sustainability-centric architectural design education. The study relied on authentic design projects, which were not attempted in any previous study. This study also postulated that the results will contribute to the development of a valid and reliable simulation method that can seamlessly enable students' architectural design experiments pertaining to the occupants' behaviors in built environments corresponding to the aims of social sustainability.

Author Contributions: Conceptualization, S.W.H., S.H.Y. and J.L.; data curation, S.W.H.; formal analysis, H.K. and S.H.Y.; funding acquisition, S.W.H. and J.L.; investigation, S.W.H., H.K. and Y.S.; methodology, S.W.H., H.K., S.Y. and S.H.Y.; project administration, J.L.; resources, H.K. and Y.S.; software, H.K. and Y.S.; supervision, J.L.;

validation, S.W.H.; visualization, H.K. and Y.S.; writing—original draft, S.W.H.; writing—review and editing, S.H.Y. and J.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) grants funded by the Ministry of Education (NRF-2016R1C1B2011274) and Ministry of Science and ICT (NRF-2020R1A2C1010421) of the Korean government.

Conflicts of Interest: The authors declare no conflict of interest.

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