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Towards a Sustainable Life
Smart and Green Design in Buildings and Community

Edited by
Mi Jeong Kim and Han Jong Jun

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Editors

Mi Jeong Kim
Han Jong Jun

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Editors
Mi Jeong Kim
Hanyang University
Korea

Han Jong Jun
Hanyang University
Korea

Editorial Office
MDPI
St. Alban-Anlage 66
4052 Basel, Switzerland

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About the Editors

Mi Jeong Kim is a professor of the School of Architecture at Hanyang University in Korea. She received her bachelor's degree and master's degree from Yonsei University and her Ph.D. at the University of Sydney. She completed a postdoc fellowship at UC Berkeley before joining Kyung Hee University. Her current research interests include convergence issues such as sensing architecture, human-computer interaction (HCI) for spatial design, virtual reality (VR) and augmented reality (AR), design education and strategies for creativity, healthy smart homes and smart communities, and cognitive studies related to design and environment. She has published international papers and books in the field and participated as guest editor and committee member of editorial boards in international journals.

Han Jong Jun is a professor of the School of Architecture at Hanyang University in Seoul, Korea. He received his Ph.D. in KCDCC (Key Centre of Design Computing and Cognition) at the University of Sydney. He completed a postdoc fellowship in the KCDCC before joining Hanyang Unversity in 1998. His research focuses on design computing in the field of architectural design and planning such as Building Information Modeling (BIM), AI in design, user-centered design based on electroencephalogram (EEG), and development of design system. He has published many international papers and conducted government research and industrial research projects in the field.

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Editorial

Towards a Sustainable Life: Smart and Green Design in Buildings and Community

Mi Jeong Kim and Han Jong Jun *

School of Architecture, Hanyang University, Seoul 04763, Korea; mijeongkim@hanyang.ac.kr
* Correspondence: hanjong@hanyang.ac.kr

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Sustainability has been a popular topic among researchers in various disciplines since its value is critical to the development of user-centered environments and populations' wellbeing. The term sustainable development was introduced by the UN as "development that meet the needs of the present without compromising the ability of future generations to meet their own needs" [1], so it often means minimizing negative impacts on the environment or decreasing the consumption of resources for maintaining the environment's stability. Green or ecological designs are often used interchangeably with environmental sustainability in the architecture domain.

The concept of sustainability extends to development related to smart buildings and healthy communities, which could support sustainable living, meeting human needs and ensuring equity. For example, sustainable living can be achieved through the adoption of smart technologies into our living spaces, wherein intelligent computing could support people's activities, or the adoption of advanced systems into our community, wherein inhabitants' wellbeing could be promoted. Furthermore, maximizing energy efficiency or intuitive interaction with technologies could enhance occupants' optimal and positive experiences in our environment.

This Special Issue aims to include contributions on occupants' sustainable living in buildings and communities, highlighting issues surrounding the sustainable development of our environments and lives by emphasizing smart and green design perspectives. After a rigorous review of the submissions by experts, fourteen articles concerning sustainable living and development have been published in this Special Issue, by authors sharing their expertise and approaches to the concept and application of sustainability in their fields. The fourteen contributions to this special issue can be categorized into four groups, depending on the issues that they address.

The first group is interested in the spatial aspect of buildings and the use of design elements to implement sustainable architecture. Rather than relying on emerging technologies for development, they seek to identify the crucial factors related to sustainability from green perspectives and apply them to the built environment to achieve an eco-friendly and sustainable lifestyle.

Lee (Contribution 1) establishes a theoretical framework for sustainable architecture from a spatial perspective. He analyzes three sustainable buildings recognized by LEED (Leadership in Energy and Environmental Design) as case studies by using an analytical tool, a visibility graph in space syntax, with a focus on economic issues. It is found that sustainable architecture can be seen to configure forms in a spatially economic way. Lee reinterprets sustainable architecture syntactically as economical—technologically, environmentally, and spatially. Similarly, Lee and Oh (Contribution 2) investigate sustainable design alternatives, such as the layout of a building complex and the width-to-depth ratios of floorplans, in terms of their energy efficiency using a simulation program. The results indicate that the shape of a building is an important design factor for the optimization of energy use in residential building complexes. For example, square housing units produce higher energy costs than the typical long and rectangular type. With a focus on climate, Ju and Oh (Contribution 3) examine the ways in which the climatic conditions have influenced the transformation of apartments in Korea and Singapore. They extract design elements and principles that have been transformed or continued from the vernacular house, which is still in use. They argue that housing culture tends to retain its identity and is important to ensure a comfortable home with the use of green design elements. Lee and Park (Contribution 4) also emphasize the potential of natural features as design elements for the optimal health and wellbeing of the elderly in smart homes. Their research suggests that smart homes for the elderly should be designed as high-quality living spaces, emphasizing biophilic experiences rather than mechanical achievement since the elderly's inherent preference for nature could be strengthened by biophilic design.

Contrary to the first group, the second group emphasizes the potential of smart technologies for sustainable design and development in buildings and the community. Most authors actively utilize advanced technologies, such as artificial intelligence (AI) and virtual reality (VR), in simulating conditions to identify the effects of specific factors on inhabitants or building performance. Based on the results of the simulation, architects are expected to make a design decision effectively and efficiently for sustainable development.

Yi (Contribution 5) proposes a computational framework to evaluate adaptive human behavior and dynamic building performance with a focus on space occupancy, energy use, and generative envelope design. The proposed simulation platform involves an agent-based model with an AI approach that can be used for design decision-making in smart architectural design, allowing designers to quickly explore various design options through the sustainable building design methodology. Hong et al. (Contribution 6) investigate the effects of human behavior simulation on the usability factors of social sustainability in architectural design education. The motivation for this research is that factors of social sustainability are not often reflected in students' projects and there is a potential for the applicability of human behavior simulation to aid social sustainability centricity in architectural design. Human behavior simulation through VR promotes the performance of projects with respect to the parameters of accessibility and safety, ergonomic usability, and social interactions. Emphasizing the potential of the data as a reference for the future Crime Prevention Through Environmental Design (CPTED) evaluation criteria, Yang et al. (Contribution 7) measure environmental factors that affect street robbery decision-making through VR with eye-tracking technology. The study demonstrates the strength of a new methodology for assessing the factors affecting criminal decision-making from a criminal's perspective, verifying the measured data quantitatively in terms of accuracy and micro-level analysis.

The third group also utilizes technologies to articulate and enforce a user-oriented approach to sustainable design and development for improved living. They seek to develop effective methods for identifying factors that can affect users' positive emotions, preferences, and experiences in architectural design. The potential of the data reflecting users' perspectives is emphasized to support decision-making processes by architects and developers in architectural design.

Ji et al. (Contribution 8) use VR with electroencephalography data for the development of a deep-learning-based stress-ratio prediction model. They analyze the amount of stress changes in a virtual space by reconstructing Adolf Hitler's new Reich Chancellery using VR, synchronizing VR equipment, and measuring the electroencephalogram (EEG) signals. The result implies that, to achieve sustainable architectural designs, it is necessary to analyze the positive indices of certain architectural design elements through the linking processes of the EEG signals, which allow architects to effectively use the design elements that support occupants' positive emotions. Jun et al. (Contribution 9) present a housing recommendation system called "SeoulHouse2Vec," which maps users and items in embedding layers and uses public big data and GIS data to analyze housing preferences. They emphasize the proposed system's support for sustainability in that the recommendation system could enable rational decision-making in both housing consumption and supply, given that both are closely related to long-term personal, social, and environmental impacts. Zhen et al. (Contribution 10) classify intelligent design in terms of the "five senses" of interaction—visual, voice, tactile, cognitive, and emotional interaction—and explore how to embody such interactive experience design in smart building systems. They argue that the proposed principle of "user-oriented" interactive experience design can ensure the security, effectiveness, and sustainability of the smart building system.

The main issue addressed by the fourth group is the increase in equitable opportunities for all in our community, and concerns for social housing, water management, and the accessibility and wellness of disabled occupants and of workers are discussed. To ensure quality of life for all, the benefits of sustainable development should be extended to vulnerable people, such as those with low incomes, those in developing countries, those with disabilities and workers.

Chung et al. review the historical development and features of social housing and discuss policy implication with a focus on social housing in Seoul (Contribution 11). To enable the more sustainable provision of social housing in the future, they argue that four issues must be considered: the role of local governments in establishing suitable ordinances depending on situations, sustainable business models for social housing projects for the diversification of supply methods, the revitalization of community based on "social mix," and the cultivation of the capabilities of social housing providers through education on social economy, housing design, construction, operation, and finance. Park (Contribution 12) explores the connection between the ownership of water and water management in a divided territory—Cyprus—to obtain an understanding of how politics are involved in water conflict, emphasizing the importance of strategies for water distribution in a sustainable community. This research highlights possible future problems for cities and regions around world through the case study of Cyprus, with a vision for a sustainable water supply and the potential for future urbanization.

In 2018, the UN released a report on disability and sustainability: Realization of the Sustainable Development Goals by, for and with Persons with Disabilities [2]. Kim and Kim (Contribution 13) investigate the effects of disabled facilities on work safety, work satisfaction, and job retention among workers with disabilities in Korea. This research is meaningful in that it demonstrates the effects of workplace disability facilities on the effectiveness of workers with disabilities with external validity using national big data. The study argues that making workplaces more accessible is important to ensuring that disabled people are not left behind, thereby resulting in the sustainable development of our society. Hwang et al. (Contribution 14) evaluate the effects of a yoga program in reducing cardiovascular disease (CVD) risk factors in workers in small workplaces, based on the assumption that workers in small enterprises are particularly vulnerable in organized health management. They assigned a yoga intervention to their experiment group for 12 weeks and found that a yoga program could be a useful intervention for workers in reducing the physical measurements of CVD risk, such as waist circumstance and diastolic blood pressure. This result suggests that a yoga program may serve as a sustainable exercise strategy for workers in small enterprises.

This special issue specifically focuses on research and case studies that make efforts to develop promising methods for the sustainable development of our environment and to identify factors critical to the application of a sustainable paradigm for quality of life from a user-oriented perspective. This collection contains new research that provides insightful ideas, cognitive perspectives, and strategic approaches for the implementation of sustainability in architectural design, energy use, housing supply, crime prevention, the workplace, and the community. All the proposed methods, models, and applications in these studies contribute to the current understanding of the adoption of the sustainability paradigm and are likely to inspire further research addressing the challenges related to constructing sustainable buildings and community, resulting in a sustainable life for all of society.

List of Contributions

1. Lee, J.H. Reinterpreting Sustainable Architecture: What Does It Mean Syntactically? *Sustainability* **2020**, *12*, 6566.
2. Lee, S.Y.; Oh, M.W. Sustainable Design Alternatives and Energy Efficiency for Public Rental Housing in Korea. *Sustainability* **2020**, *12*, 8456.
3. Ju, S.R.; Oh, J.E. Design Elements in Apartments for Adapting to Climate: A Comparison between Korea and Singapore. *Sustainability* **2020**, *12*, 3244.
4. Lee, E.J.; Park, S.J. A Framework of Smart-Home Service for Elderly's Biophilic Experience. *Sustainability* **2020**, *12*, 8572.
5. Yi, H. Visualized Co-Simulation of Adaptive Human Behavior and Dynamic Building Performance: An Agent-Based Model (ABM) and Artificial Intelligence (AI) Approach for Smart Architectural Design. *Sustainability* **2020**, *12*, 6672.
6. Hong, S.W.; Kim, H.; Song, Y.; Yoon, S.H.; Lee, J. Effects of Human Behavior Simulation on Usability Factors of Social Sustainability in Architectural Design Education. *Sustainability* **2020**, *12*, 7111.
7. Yang, J.W.; Kim, D.; Jung, S. Eye-Tracking Technology to Measure Environmental Factors Affecting Street Robbery Decision-Making in Virtual Environments. *Sustainability* **2020**, *12*, 7419.
8. Ji, S.Y.; Kang, S.Y.; Jun, H.J. Deep-Learning-Based Stress-Ratio Prediction Model Using Virtual Reality with Electroencephalography Data. *Sustainability* **2020**, *12*, 6716.
9. Jun, H.J.; Kim, J.H.; Rhee, D.Y.; Chang, S.W. "SeoulHouse2Vec": An Embedding-Based Collaborative Filtering Housing Recommender System for Analyzing Housing Preference. *Sustainability* **2020**, *12*, 6964.
10. Li, Z.; Zhang, J.; Li, M.; Huang, J.; Wang, X. A Review of Smart Design Based on Interactive Experience in Building Systems. *Sustainability* **2020**, *12*, 6760.
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12. Park, E.J. Strategy of Water Distribution for Sustainable Community: Who Owns Water in Divided Cyprus? *Sustainability* **2020**, *12*, 8978.
13. Kim, E.J.; Kim, I.; Kim, M.J. The Impact of Workplace Disability Facilities on Job Retention Wishes among People with Physical Disabilities in South Korea. *Sustainability* **2020**, *12*, 7489.
14. Hwang, W.J.; Kim, J.A.; Ha, J.S. Effects of a Yoga Program in Reducing Cardiovascular Disease Risk Factors in Workers of Small Workplaces: A Pilot Test. *Sustainability* **2020**, *12*, 10038.

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2. United Nations. Realization of the Sustainable Development Goals by, for and with Persons with Disabilities. Available online: https://www.un.org/development/desa/disabilities/wp-content/uploads/sites/15/2018/12/Executive-Summary-11.29-2.pdf (accessed on 10 January 2021).

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Article

Reinterpreting Sustainable Architecture: What Does It Mean Syntactically?

Jae Hong Lee

Department of Architecture, Gachon University, Seongnam 13120, Korea; zenoar@gachon.ac.kr;
Tel.: +82-31-750-5298

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Abstract: How can sustainable architecture be described spatially? Is there any way of looking at sustainable architecture from a spatial perspective? This paper aims to explore whether a syntactical viewpoint would be an appropriate focus, and attempts to address how a configurational approach contributes to our understanding of sustainable architecture. To explore the possible theoretical framework in understanding sustainable architecture from a spatial perspective, three buildings (namely, Olympic House, SK Chemicals R&D, and the Epson Innovation Center), which are recognized as the most sustainable buildings by Leadership in Energy and Environmental Design and Comprehensive Assessment System for Built Environment Efficiency, are selected and analyzed by using visibility graph analysis, a useful analytical tool in space syntax. The in-depth theoretical studies and literature reviews have suggested that the atria in sustainable architecture play a substantial role in maximizing energy efficiency, minimizing negative impacts on the environment, and generating spatial integration. Thus, it is concluded that sustainable architecture is economical in technological, environmental, and spatial ways as well.

Keywords: sustainable architecture; space syntax; partitioning theory; total depth; intelligibility; movement economies

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1. Introduction: The Problem of Sustainable Architecture

Space has long been a key issue in areas of architectural research, and this topic attracts the attention of many different disciplines, such as cognitive science, environmental psychology, environmental graphic design, and even sociology. That is, a built space not only works as a physical shelter, but it is also a "meaningful and informative formation expressive of the culture and lifestyle of different societies and of the transformations that the social structure has experienced" [1] (p. 54.1). It is the distinctive characteristics of social systems that embody spatial formations, and spatial formations, in turn, can be seen as "visual symbols of societies" [2]. If this is so, what is the problem in understanding sustainable architecture?

It has been admitted that sustainable architecture is an architecture which aims to maximize energy efficiency by using the most modern technologies and, in turn, minimize negative impacts on the environment. In addition, there are diverse viewpoints regarding sustainable architecture that go beyond such a technological viewpoint. Guy and Farmer (2001) present six alternative logics of ecological design—eco-technic logic, eco-centric, eco-aesthetic, eco-cultural, eco-medical, and eco-social—and one of the reasons why they try to identify such aspects is to argue that sustainability is not an uncontested single homogeneous concept, but should be understood as an interpretative flexible one, because "debates about sustainable architecture are shaped by different social interests, based on different interpretations of the problem, and characterized by quite different pathways toward a range of sustainable futures" [3] (p. 146). Susan Maxman also suggests that sustainable architecture is not "a prescription" but "an approach" and "an attitude," and therefore, it "should be just architecture" (cited in [3] (p. 140)). Further, Guy and Moore contend that "we need to recognize and analyze green buildings as a series of contingent hybrids, an understanding of which is inseparable from the encounter with the people and places that shaped their design and development" [4] (p. 3). In this way, sustainable architecture should be seen not only as an ecological context but also as an activity of constituting a spatial layout and forming human behaviors.

However, it is not clear how strongly sustainable architecture is related to spatial formations, and how it characterizes spatial configurations. This paper, therefore, aims to shed light on creating a new framework of viewing sustainable architecture from a spatial perspective, and to provide a substantial understanding by looking at in-depth literature reviews and case studies.

2. Sustainable Architecture

As is well known, the term sustainable development was introduced in the Our Common Future report of the Brundtland Commission in 1987, and defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." In particular, the issue of sustainable development was widely accepted as one of the important matters which are central to our present and future as well. Considering its significance, the United Nations Conference on Environment and Development held in Rio de Janeiro in 1992 took the first step of communicating sustainable development, and generating substantial agreement on what to do and how to reach sustainable standards. In 2002, the World Summit on Sustainable Development identified that poverty, which is one of the threats, should be reduced to overcome hindrances of sustainable development. The underlying purpose of sustainable development is to help developing countries reasonably manage their natural resources and to utilize them without depleting these resources, and make them ecologically and economically balanced. As Dr Brundtland said, "healthy life is an outcome of sustainable development, as well as a powerful and undervalued means of achieving it," and we need to understand "health as a precious asset in itself, and as a means of stimulating economic growth and reducing poverty" [5]. Therefore, sustainable development is strongly related to a better life (or sustainable living).

In this, Vallero and Brasier stress that "we have a core ethic of intergenerational equity," and "future generations should have an equal opportunity to achieve a high quality of life" [6] (p. 175). They go further to say that this goal, a sustainable global ecological and economic system, is achievable "in part by the wise use of available resources," and thus, sustainable development can only be achieved through "green engineering" [6] (p. 175).

Green engineering is defined as "the design, commercialization and use of processes and products that are feasible and economical while reducing the generation of pollution at the source and minimizing the risk to human health and the environment." In practice, green engineering can be implemented by "principles of green programs, such as 'waste prevention,' 'safe design,' 'low-hazard chemical syntheses,' 'renewable material use,' 'avoiding chemical derivatives,' 'selection of safer solvents and reaction conditions,' 'improved energy efficiencies,' 'design for degradation,'" and so on [6] (pp. 180–182). In short, the primary aim of green engineering is to achieve "waste reduction," "materials management," "pollution prevention," and "product enhancement." In the case of building design, green architecture begins with a close look at given site conditions or environmental characteristics, because it is believed that a given building site is not empty but full of fragile macrobiotics, microclimate, and urban fabrics as well. Therefore, green architecture can be described as the "means of allowing people to become more in touch with the environment in which they live . . . [and incorporating] natural landscapes into the design of the building which gives people a better connection to the land" [6] (p. 168).

Similar to the conception of green architecture, Guy and Farmer try to understand sustainable architecture in terms of not an absolute or incontestable conception, but a relative or variant one. This is because "the concept of a green building is a social construct," and therefore "individuals, groups, and institutions embody widely differing perceptions of what environmental innovation is about" [3] (p. 140). Considering this, they analyze some studies of completed buildings and conduct a literature review of books, articles, and reports which are primarily concerned with sustainable, environmental, ecological, or green buildings, and they suggest a total of six logics: eco-technic, eco-centric, eco-aesthetic, eco-cultural, eco-medical, and eco-social. First, the key feature of the eco-technic logic is its "globalized viewpoint" which is concerned with "the universal, global environmental problems of climate change, global warming, ozone layer depletion, and transitional pollution," and, in architectural practice, the representative issue is "efficiency," so that the design strategy is based on "modern and high-technology buildings that attempt to maximize the efficiency of building in spatial, construction, and energy terms" [3] (pp. 141–142). Second, the eco-centric logic proceeds from the recognition of "the dynamic interaction between the living and nonliving as a community of interdependent parts," so that this logic encompasses "nonliving objects and ecological systems" [3] (pp. 142–143). The main approaches to building begin with inquiring whether to build at all. If necessary, the main objective of erecting a building is focused on reducing its ecological footprint. Third, the eco-aesthetic is the view that the role of sustainable architecture should act to "inspire and convey an increasing identification with nature and the nonhuman world" [3] (p. 143). This logic emphasizes "individual creativity and a liberated imagination combined with a romantic view of nature that rejects Western rationalism, modernism, and materialism," so that the solution to the environmental crisis requires "a shift from utilitarian values to a view in which aesthetic and sensual values play a prominent role" [3] (p. 144). On the contrary, the eco-cultural stresses "a fundamental reorientation of values to engage with both environmental and cultural concerns," so that the key issue of this logic is to preserve "a diversity of existing cultures" [3] (p. 144). Unlike the eco-technic logic, this one argues for "decentralization", and focuses on local characteristics. Within this logic, sustainable architectural approaches correspond to the "cultural values of a particular place or people." The eco-medical construct is mainly concerned with sustaining individual health, so it focuses on "the adverse impacts of the built environment and the causes of stress that engender health problems, both physical and psychological" [3] (p. 145). In building design, this logic is dealt with particularly by reducing chemical pollution from synthetic materials used in the interior of the building. Lastly, the eco-social aspect addresses that "the root cause of the ecological crisis stems from wider social factors", so it proposes "the decentralization of industrial society into smaller, highly self-sufficient, and communal units, working with 'intermediate technologies that are based on an understanding of the laws of ecology'" [3] (pp. 145–146).

Taken as a whole, we have gone through a literature review, from the definition of sustainable development to those diverse aspects which play an important role in understanding sustainable architecture, via green engineering, which is mainly concerned with increasing efficiencies with the help of technological advances and finding a better way of building function itself. However, those aspects hardly cover the spatial issue which is an integral part of the architecture. Specifically, they seldom provide us with a useful framework to understand how strongly sustainable development is related to the pattern of spaces or spatial configuration.

3. Configurations and Space Syntax

3.1. Configurational Approach in Understanding Built Forms

The term configuration refers to "the particular arrangement or pattern of a group of related things," and Hillier et al. (1987) take this a step further, under a spatial consideration, to argue that configuration can be defined as, at least, "the relation between two spaces taking into account a third, and, at most, as the relations among spaces in a complex taking into account all other spaces in the complex" [7] (p. 363). Spatial configuration, therefore, is a way to constitute spatial patterns and forms. For example, say you are asked to build a shelter like a hut. Working on this, you realize that even though it can be constructed in a very simple way, the act of both creating boundaries of inside or outside and partitioning into sub-spaces is logical and sociological as well. It is because the drawing of these boundaries "establishes not only a physical separateness but also the social separateness of a domain," and therefore "the logical distinction and the sociological distinction . . . emerge from the act of making a shelter even if they are not intended" [8] (p. 16). Human activities, such as encountering, congregating, avoiding, interacting, dwelling and conferring, are "attributes of patterns" which are "formed by groups or collections of people" [8] (p. 20), and these activities are carried out in spatial configurations. Therefore, architecture is understood as the relation between space and people.

In the article *Configurations and urban sustainability* (2004), Akkelies van Nes has a slightly different approach from that of Hillier: he stresses that urban morphology is not an object but a process within which a continual transformation of urban cultures and economies has taken place, and urban layout, as an ongoing product, affects a certain kind of behavior both socially and economically. This transformation is, effectively, driven by the conception of sustainable development which is one of the major issues in the Brundland report of 1987 and the 1992 Earth Summit in Rio de Janeiro. Based on this idea, van Nes asserts that urban sustainability takes account of "compactness," and the compact city model is the most sustainable way of "living and low energy use for transportation" [9] (p. 413). In particular, both movement and interaction are important issues in understanding urban compactness. For example, retail shops, which are one of the integral parts of urban activities, are strongly correlated with the configurational features of urban layout: the more the urban layout is integrated, the more shoppers' movement is attracted. In other words, the urban layout has a deterministic influence on attracting people's movement, and placing retail shops accordingly as well.

3.2. Space Syntax

Space syntax is "a set of techniques for the presentation, quantification and interpretation of spatial configuration in buildings and settlements" [7] (p. 363), and it is considered an analytical tool for describing spatial formations, identifying the pattern of people across configurational characteristics, and understanding social meanings.

Space syntax represents spaces in many ways, such as convex space, axial line or isovist, and these representations are markedly ecological because they are strongly interrelated with our behaviors. In Figure 1, for example, people move through spaces in lines and this movement is drawn by an axial line; people interact in a convex space which is described by a polygon; and, lastly, people see through spaces and get a "visual field at a certain standing point" [10] (p. 36), and this visual field is called isovist, defined as "the set of all points visible from a given vantage point in a space" [11] (p. 47). In particular, the two former representations (i.e., convex space and axial line) are quantified and explained in terms of depth.

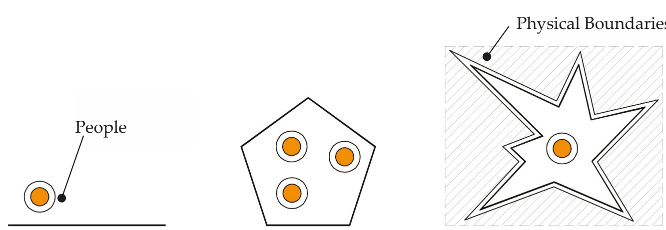


Figure 1. Space is not a background but an intrinsic aspect of human activity. (redrawn from the original image from Figure 1 [12] (p. 5)).

Therefore, how can we understand depth in relation to our behaviors and spatial configurations? For this, we need to look at a rural French house. Figure 2 shows a ground floor plan and justified graphs. The justified graph is the most useful device not only for showing 'configurational properties in visual form', but also for illustrating in a numeric way how deep or shallow a certain space might be [13] (p. 30). Simply, this graph can be drawn in this way: a circle, which is selected as a root, is put at the base; all circles, which are directly connected to the root, are aligned above the root, meaning depth 1; then all circles, which are directly connected to those at depth 1, are aligned above them again at depth 2; and one repeats this process until all depth levels from the root are explained. After having completed drawing the graph, we can obtain the total depth from the root by adding up the numbers which are computed by multiplying the number of circles by the depth level: in Figure 2(b-1), for example, the total depth from the root, the *grande salle* (reception room), is 31 ($31 = 0 \times 1 + 1 \times 1 + 2 \times 2 + 3 \times 3 + 4 \times 3 + 5 \times 1$). Like this, the total depths from outside and the *salle commune* (everyday communal living and cooking space) are measured, and they are 21 and 18 accordingly (Figure 2(b-2,b-3)).

The ground plan, justified graphs drawn from different roots, and the total depth values give us important configurational characteristics. The space of the *grande salle* is located just by the main entrance, which leads to a vestibule and the upper floor, so it could be thought that it is significant because of its direct accessibility from the outside. In terms of the depth conception, however, this space has a total of 31 depths, and it can be thought overall that it is located in the most remote part of the house, and, hence, is hard to reach by family members. On the other hand, the *salle commune* has a total of 18 depths, and it is relatively shallow and thus recognized as a central place. Although this rural house shows a simple spatial composition, the *grande salle*, which is mainly used as a reception room for visitors, is intentionally placed far from the '*salle commune*', which is a central place for family. Therefore, it is noted that the configurational properties of space, in particular the total depth, are seen as a powerful way of understanding how spaces are arranged and how the spatial formation works.

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

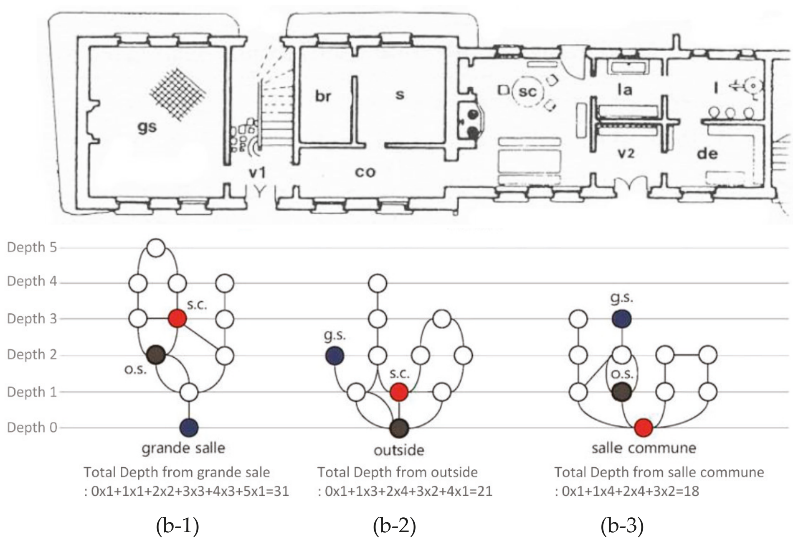
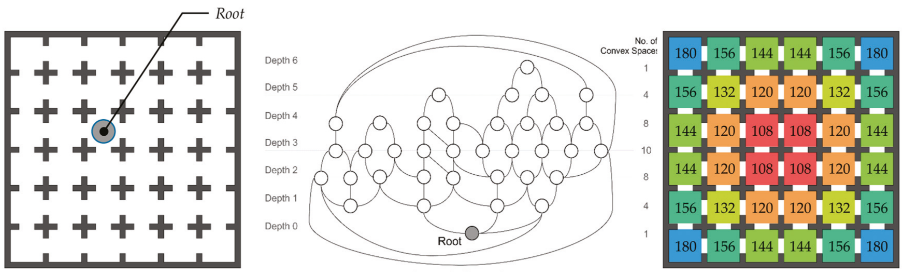


Figure 2. (**a**) Ground floor plan of a rural French house; (**b**) Justified graphs of three primary spaces (grande salle, outside, and salle commune) (reproduced from Figure 1 [13] (p. 31)).

3.3. Partitioning Theory: Gaining or Losing Total Depths

We need to take a step further and ask in what way configurational properties affect depth gains or losses, or, in turn, how depth gains or losses determine spatial formations. Regarding these questions, Hillier suggests partitioning theory. Consider a simple six by six half-partitioned complex, wherein a total of 36 cells are placed within a square boundary, and all cells are open to each other (Figure 3a). As we already know from the analysis of the rural French house, the total depth values for each cell can be obtained from the justified graph. For example, Figure 3b shows a justified graph of a certain root in the layout of 6×6 cells, and a total number of 108 depths is measured ($108 = 0 \times 1 + 1 \times 4 + 2 \times 8 + 3 \times 10 + 4 \times 8 + 5 \times 4 + 6 \times 1$). When we repeat the drawing of the justified graphs and computing the depths for the other cells, depths can be obtained (see Figure 3c). One of the interesting findings in this analysis is that there is a pattern. That is, the central four cells have the least number of total depth values, 108, while the corner cells have the greatest number, 180. As Hillier notes about this, it is clear that "the differences between the cells are due to the relation of the cell to the boundary of the complex," and "Corner cells have most depth, center edge rather less, then less toward the center" [8] (p. 223). This means that the boundary of the complex works as bars so that the cells located at the corner have more depths than the ones at the center. When we add up all of the total depths of the cells, this spatial formation has 5040 depths.

Placing a bar between cells leads to gaining total depths. Hillier explains the barring and gaining depth relation in terms of four principles: centrality, extension, continuity, and linearity [8].



Layout of 6 × 6 Cells — (**a**)

Total Depth from the Root: 0×1+1×4+2×8+3×10+4×8+5×4+6×1=108 — (**b**)

Total Depth: +5,040 — (**c**)

Figure 3. (**a**) Default layout of 6 × 6 cells open to each other; (**b**) Example of justified graph and total depth from the selected *Root*; (**c**) Total depth values of each cell on color schemes (red ones such as the four cells in the center have the least total depth, 108, whereas blue, like the corner four cells, have the most depth values, 180) (redrawn from Figure 8.2(a) [8] (p. 224)).

3.3.1. Principle of Centrality

The principle of centrality dictates that the depth gain will be maximized when a bar is at or near the center, rather than at the edge. For example, when we place a bar in the leftmost horizontal top line in Figure 4(a-1), the total depth is increased from 5040 to 5060—an additional 20; when locating the bar one to the right, the number is increased from 5040 to 5072 (Figure 4(a-2)), and on placing the bar at the center, the number rises from 5040 to 5076—a gain of 36 (Figure 4(a-3)). These depth gain effects of barring from the edge to the near or center are called the principle of centrality: "more centrally placed bars create more depth gain than peripherally placed bars" [8] (p. 234).

3.3.2. Principle of Extension

Suppose that a second bar is located on an adjacent line. Figure 4(b-1–b-4) show that when the two bars are getting closer, the total depths will be increased from 5040 to 5084, 5100 and 5120—a total depth gain of 44, 60 and 80, respectively, from the default layout. When two bars are moving together toward the near or the center, the total depths will be greater, a gain of 92. These systematic effects, as Hillier suggests, are called the principle of extension: "barring longer lines creates more depth gain than barring shorter" [8] (p. 228).

3.3.3. Principle of Continuity

This principle is about the effect of continuous bars. When two bars are linked, the total depths in the aggregate will be increased from 5040 to 5168—an additional 128 depths in total from the default layout, more than the scenario where two bars are separated, which results in an additional 68 (see Figure 4(c-1,c-2)). However, when we look at Figure 4(c-2–c-4), it is quite interesting that when a two-bar L-shape is moving diagonally from the upper left corner to the lower right, the additional total depth gains are less (i.e., 128, 108, 80). Therefore, "continuous bars create more depth gain than non-continuous bars", because the non-continuity of bars provides a way through via the shortest path [8] (p. 234).

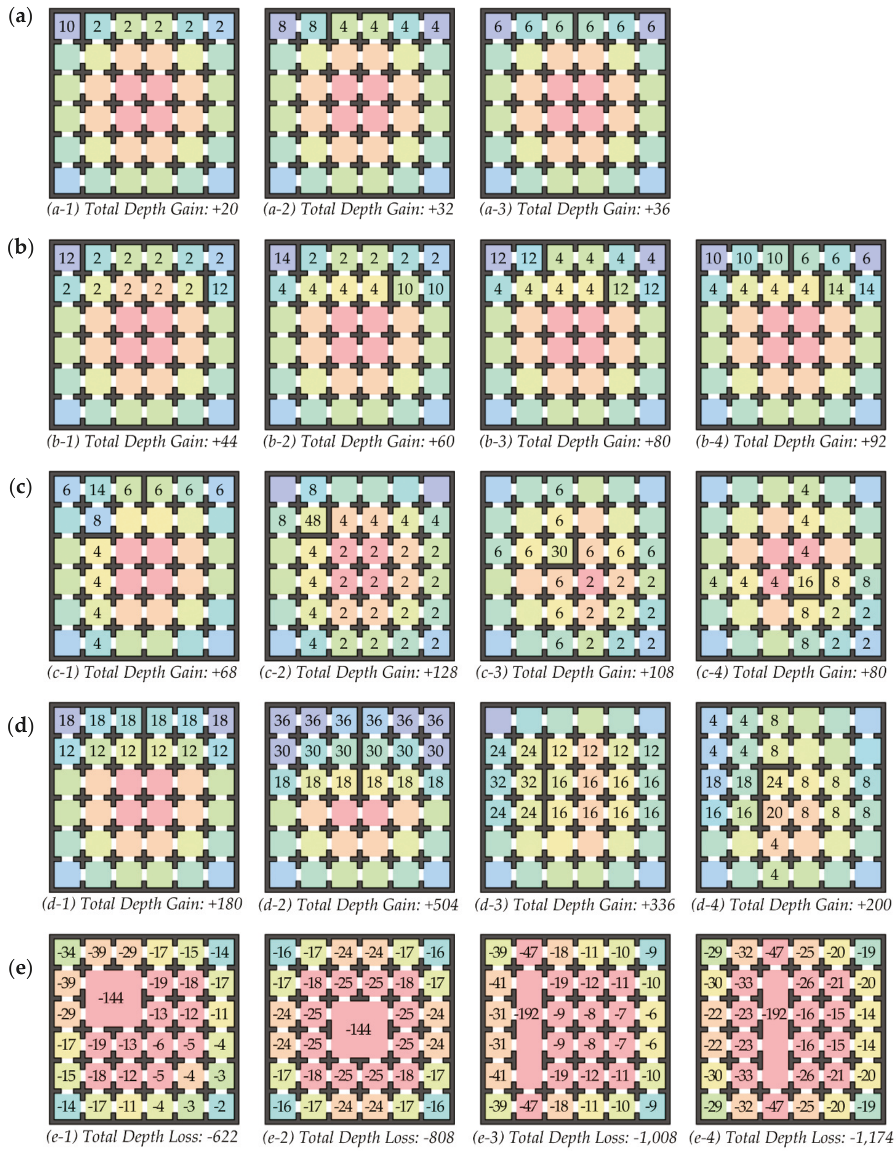


Figure 4. (**a**) Principle of centrality and depth gain effects; (**b**) Principle of extension and depth gain effects; (**c**) Principle of continuity and depth gain effects; (**d**) Principle of linearity and depth gain effects; (**e**) Subtracting partitions and depth loss effects (the numbers depicted on cells stand for additional depth gains, compared with the default layout where all cells are open to each other) (regenerated from Figure 8.3–8.9 [8] (pp. 225–237)).

3.3.4. Principle of Linearity

The principle of linearity is the one whereby "linearly arranged continuous bars create more depth gain than coiled or partially coiled bars" [8] (p. 234). For instance, the number of total depths in which two bars are linearly connected in Figure 4(d-1) is increased from 5040 to 5220, an additional 180.

When three bars are placed in Figure 4(d-2), the total depths gain is increased to 5544. When we look at Figure 4(d-3,d-4), it is obvious that the linearly placed bars result in more depth gains than the bent ones. This principle is the most effective way of increasing total depths. This is because, according to Hillier, “it is the most economical way of constructing an object requiring the longest detour from cells on either side to the other,” and because “the longer the bar the more it has the effect of increasing the number of cells on either side of it” [8] (p. 232).

3.3.5. Losing Total Depths

Placing internal bars can affect the process of gaining total depths, and the effects always follow the four principles of centrality, extension, continuity, and linearity. On the other hand, we can imagine that there are larger spaces, such as courts or corridors, within a given spatial formation. In Figure 4e, larger spaces are created by eliminating the two-thirds partitions in the adjacent four cells. The larger spaces are made up of the same numbers, but the only differences are the shapes and locations: specifically, in Figure 4(e-1,e-2), the space is a square, and one is located at the upper left corner, while the other is at the center; Figure 4(e-3,e-4) is a rectangle, and one is placed at the near left edge, while the other at the center. As already noted, there are quite substantial distinctions between the figures. The most depth loss happens in Figure 4(e-4), from 5040 to 3866 (a loss of 1174), whereas the least depth loss is found in Figure 4(e-1), from 5040 to 4417—a loss of 622. Contrary to the partitioning theory, the total depth losses will be increased as larger spaces are placed at the center rather than at the edge or corner. Besides, the depth losses are greater when larger spaces are arranged in a linear way.

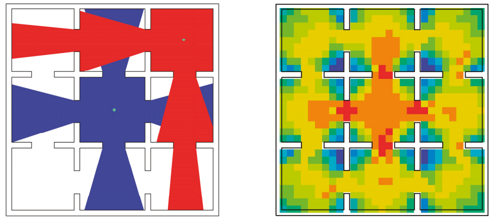
4. Research Methodology and Cases

4.1. Research Methodology

We have taken a look at the idea of partitioning theory and the theoretical scenarios of total depth gains and losses by manipulating partitions through the convex map of the six by six half-partitioned complex. In theory, convex space is a powerful approach to describing and representing spaces in a spatial layout. In practice, however, it is not easy to convert all spaces into convex spaces. In Figure 5, for instance, the spaces have several different shapes: some of them follow geometric forms like the meeting rooms in the SK Chemicals R&D Center, while others take idiosyncratic forms like the offices in Olympic House. In the Epson Innovation Center, moreover, the atrium consists of several small convex spaces due to the dispersed vertical access points, such as elevators and stairs. In this, the convex map is little used in analyzing a large and complicated floor plan, and thus, visibility graph analysis (VGA) is used in buildings.

The idea of VGA is derived from the conception of the isovist. However, the isovist is not suitable for looking into the whole spatial layout of a building, because, as we have mentioned before, “the geometric formation of the isovist represents purely local properties of space” and “the visual relationship between the current location and the whole spatial environment is missed” [14] (p. 104). In relation to this, Turner suggests a VGA which allows us to understand all of the configurational properties (see Figure 5). The first step of VGA is to make a grid of point locations, and the grid spacing is normally set to 0.6 m by 1.0 m, which corresponds to human scale. After having completed the grid setting, VGA is performed using the depthmap X program (depthmapX-0.6.0_win64 version).

Similar to the convex map analysis, VGA calculates the visual depth of each point location. Here, the visual depth is defined as a “measure of the shortest path through the graph,” and it provides different measures, such as visual step depth, visual connectivity, visual mean depth, and visual integration [15] (pp. 10–17). In VGA, we can arrive at both a local and a global analysis of the graph. The local one sees how a node is directly connected to other nodes, and this measure includes visual step depth and connectivity. On the other, the global measure looks at how a node is related to the whole, and this is understood by visual mean depth and integration.



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

Figure 5. (**a**) Two isovists on a 3 × 3 complex; (**b**) Visibility graph analysis (VGA) with integration values on a 3 × 3 complex on a 0.7 m-grid (source from Figure 2.4 [10] (p. 42)).

As a local feature, visual step depth can be seen as "the number of turns that it takes to get from the current location to any other location" within the spatial layout. Visual step depth gives an idea of how easy or difficult it is to reach the other locations. Visual connectivity is described by the total number of direct connections to the others from a certain node. Therefore, this measure can lead us to have instant meetings or casual talks with people locally.

Visual mean depth, as one of the global features, describes the mean number of a certain node to all others within the system. If a node has a relatively high mean depth value, it is placed in remote areas. Visual integration value looks at how an individual node is related to the whole. This means that it enables us to explore how many nodes should be passed through to reach the whole system from the individual node. If a certain node within a spatial layout has a high integration value, it can be said that it is integrated or shallow. Conversely, if a node has a low value, this indicates that it is difficult to get to this node from the others, so it is referred to as segregated or deep.

Once these values are allocated to all nodes, they are grouped into five from the highest to the lowest. These groups, then, are illustrated by different colors from red to blue. Red stands for the most connected and integrated nodes, and the lowest values of step depth and mean depth. On the other hand, blue stands for the most disconnected and segregated ones, and the greatest values of step depth and mean depth. These colors suggest important ideas of "where the most integrating spaces are," "what they relate to in the system," and "what type of pattern the strong integrating spaces make" [2] (p. 115). Furthermore, these ideas make us think of how intelligible or unintelligible a spatial layout would be [8]. If a spatial system is intelligible, what we see on a node at a local level can lead us to understand what we cannot see at a global level, even though the amount of information is scant. Therefore, it can be said that the spatial morphology is predictable and apprehensible. However, if a spatial layout is unintelligible, it is hard to comprehend the relation of the local to the global. Therefore, it is expected that the morphology is not predictable. Intelligibility can be measured by the correlation between "the pattern of connectivity" and "that of integration" [8,10].

4.2. Cases

The three buildings we have chosen to describe are Olympic House, the SK Chemicals R&D Center, and the Epson Innovation Center. We need to make the point that these buildings do not represent the "ideal" sustainable buildings, and their physical performance is not an issue discussed in this article even though it has become a central concern in contemporary sustainable architecture.

In Table 1, Olympic House (OH) was newly designed as the International Headquarters of the International Olympic Committee (IOC) and construction was completed in June 2019. Before having this new headquarters, employees of the IOC were split into several buildings across Lausanne, Switzerland, and this geographical split brought about an inefficiency. For this reason, the IOC had decided to build a new headquarters big enough to accommodate all staff. The IOC had seen this new building as "an opportunity to craft a headquarters that served not only as an office space but also as a representation of their brand" [16] (p. 2). From this perspective, a "five-ring central staircase" is designed in the heart of the building, and this five-story atrium leads directly to transparent and collaborative working areas across the floors (see Figure 6a). Notably, this atrium is called the "Unity Staircase," because it strengthens "connectivity and collaboration between the different sections of Olympic House while simultaneously representing the IOC's mission statements of Unity in Diversity, Universality and Solidarity" [16] (p. 4). Regarding sustainability, this building has been awarded a Platinum rating and received the most points out of any Leadership in Energy and Environmental Design (LEED) v4 Building Design and Construction project up until now. Specifically, it is designed to provide every employee with access to outdoor views, and, in turn, to bring in natural daylight to office areas through the exterior and atrium. It reduces resource consumption by means of low-flow faucets and toilets, a rainwater harvester, enhanced insulation, heat recovery system, Light Emitting Diode (LED) lighting, a natural ventilation system through the atrium, and so on.

Table 1. Building facts and green features of three cases.

Cases	Main Features
Olympic House	• Located on the shores of Lake Geneva in Lausanne, Switzerland • Total floor area: 25,000 m^2 • Total six floors (basement + ground floor + three office floors + roof terrace) • Opened in June 2019 • Energy rating: Platinum awarded (93/110) from LEED v4 BD + C [1] • Green features - Providing access to outdoor views and bringing in natural daylight to the office through windows and atrium - Reducing resource consumption (i.e., low-flow faucets and toilets, rainwater harvester, enhanced insulation, heat recovery system, Light Emitting Diode (LED) lighting, natural ventilation system through the atrium, etc.)
The SK Chemicals R & D Center	• Located in Seongnam, South Korea • Total floor area: 47,652 m^2 • Total 14 floors (5 basement floors + ground floor + 8 office and research floors + roof garden) • Opened in September 2010 • Energy rating: Platinum awarded (55/69) from LEED v3 BD + C • Green features - Providing access to green areas such as roof garden and wall fountain - Reducing energy consumption (i.e., triple-layered low-e glass, enhanced insulation, micro-louver system, LED lighting, etc.) - Earning energy from nature using a Building-integrated Photovoltaics (BIPV) system, natural ventilation through the atrium, geothermal heat pump, rainwater harvester, etc.)
The Epson Innovation Center	• Located in Nagano, Japan • Total floor area: 53,372.05 m^2 • Total seven floors (seven experiment and research floors) • Opened in February 2006 • Energy rating: S (excellent) awarded from CASBEE-NC [2] 2008 v.0.5 • Green features - Natural ventilation system using automatic ventilation windows and atrium - Using ground heat by a cooling and heating trench system - Applying energy-saving technologies such as photovoltaic power generation, a vacuum type solar water heater, water saver, using rainwater, recycling of air-conditioning drainage, etc. - Light duct system

[1] LEED v4 BD + C = Leadership in Energy and Environmental Design version 4 Building Design + Construction established by the U.S. Green Building Council (USGBC). [2] CASBEE-NC = Comprehensive Assessment System for Built Environment Efficiency—New Construction developed by Japan Sustainable Building Consortium (JSBC).

The SK Chemicals R&D Center (SK), as the second case, is located in Seongnam, South Korea, and opened in 2010. This building is divided into three sub-blocks: a northern block designed for staff who work in administration; a southern one for researchers working for developing technologies; and a central one linking to the northern and southern blocks. Specifically, the central block is designed as an atrium, which provides a splendid view of a vertical and spacious indoor environment (see Figure 6b). This center has a total of 14 floors: 5 basement floors, a ground floor, 8 office and research floors, and a roof garden. The ground floor serves as a welcoming place where all staff and visitors move around freely, and have meetings in several meeting rooms placed in the southern block or a staff lounge in the northern. This building received the Platinum Certificate from LEED v3 Building Design and Construction in 2011 [17]. Regarding green features (see Table 1), it provides good access to green areas such as a roof garden, wall fountain, green shaft and interior wall greening; energy-consumption-reducing technologies are applied across the building, such as a triple-layered low-e glass curtain walls, enhanced insulation, a micro-louver system on the top floor of the atrium, LED lighting, and vertical and horizontal louvers on the exterior walls. This center has enhanced energy-earning technologies from nature, such as a Building-Integrated Photovoltaics (BIPV) system, natural ventilation through the atrium, a geothermal heat pump, and a rainwater tank.

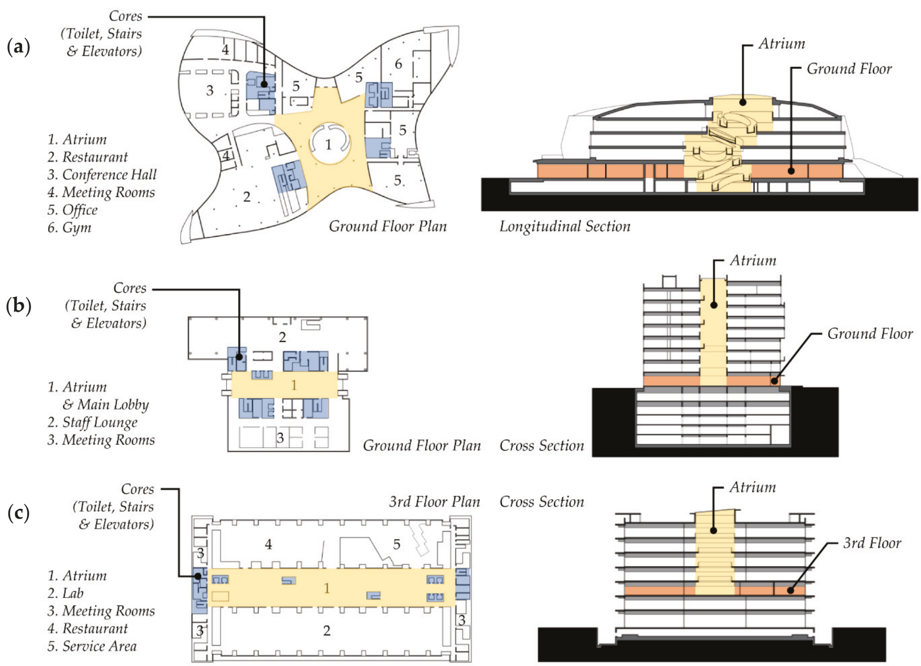


Figure 6. Plans and sections of cases: (**a**) Olympic House: IOC Headquarters; (**b**) The SK Chemicals R & D Center; (**c**) The Epson Innovation Center.

The Epson Innovation Center (EI) is located in Nagano, Japan, and was completed in 2006. This center is a research facility for developing next-generation information-related products and appliances. This building has a total of seven floors, and all floors are composed of an experiment and research lab, except the second one where service facilities and the research office are located. In the central part of this building, there is an atrium starting from the third floor to the top, and this atrium is intentionally designed to promote closer relationships between researchers. Interestingly, service areas are located on the second floor instead of the ground floor (see Figure 6c). In terms of sustainability (see

Table 1), this center received a high score from CASBEE-NC 2008 (v.0.5), which is an evaluation and assessment system developed by the Japan Sustainable Building Consortium [18], and this building is characterized by the following criteria: a natural ventilation system using automatically opening and closing windows, a wind-based ventilation induction plate, and a backdraft damper installed in the atrium; a cooling and heating trench system which draws in fresh air and delivers it to the interior through a one-kilometer-long trench; a light duct system introducing daylight into the building, particularly the restaurant; and energy-saving technologies such as photovoltaic power generation, a vacuum type solar heater, a water saver, and the recycling of air-conditioning drainage.

Having briefly reviewed these buildings, it has been found that they are considered highly efficient buildings. One of the fascinating things is that each building has an atrium in the central area, although they are located in geographically distinct areas across the world and have different functions. This indicates that the atrium plays a substantially important role in creating energy-efficient buildings. For instance, the vertical openness from the ground floor to the top enables natural ventilation, and also this characteristic allows daylight into the central area of the building. Indeed, the atrium makes buildings more sustainable, and also makes us healthier. However, it is unclear how this atrium works spatially, or how it helps us to achieve sustainable life. To answer this architecturally fundamental question, space syntax was used in each of the cases.

5. Syntactical Analyses and Discussion

5.1. VGAs: Visual Connectivity, Integration, Mean Depth, and Step Depth

Figure 7 shows the syntactical results of the three buildings. The grid spacing of all cases was set equally by 1.0 m, and only the floor where an atrium begins in the building was investigated. All spaces, such as toilets, stairs, elevators, facility rooms and vestibules, were included, except for furniture. Through the VGA, the depthmapX-0.6.0 space syntax program, which is maintained and developed by UCL's Space Syntax Laboratory, was used.

In the visual connectivity, it can be recognized that there is a strong pattern in terms of spatial connectedness (see Figure 7a–c). That is, the larger spaces colored in red—a restaurant in Olympic House (OH), a staff lounge in the SK Chemicals R&D Center (SK), and a lab in the Epson Innovation Center (EI)—have higher numbers of direct connections, and, in particular, the lab in the EI is the most connected space in this connectivity analysis. The smaller spaces colored in blue—meeting rooms, stairs, elevators, and restrooms in all cases—have the lowest numbers. From this result, we can understand that the larger spaces, compared to the smaller ones, offer an opportunity for social interaction because of their greatest total number of direct connections to others. However, when we look carefully at this result, we see something interesting: unlike the restaurant in OH and the staff lounge in the SK, the lab in the EI is used not as a congregational space but a research one. Of course, there is a congregational space in the EI: that is, a restaurant opposite the lab. This result can be explained in this way: the lab is larger than the atrium and the restaurant, and there are no additional architectural elements such as stairs, elevators, or partitions for this reason, the lab tends to be highly connected, with the highest number (max. 1848).

The visual integration analysis at the global level, however, gives us a different story (see Figure 7d–f). In the cases of OH and the EI, it can be said that the atria, rather than the restaurant and the lab, are the most integrated places, and in particular, this high integration value extends to the corridor between meeting rooms, and a conference hall in OH and the lab in the EI. The staff lounge rather than the atrium in the SK is still highly integrated at this level.

In the visual connectivity and visual integration, we see there is a dynamic change in terms of different levels: at a local level, social interactions take place in the congregational spaces, whereas, on a global level, the atrium is considered an important place in understanding the spatial structure and navigating other places across the building. In the case of the SK, however, the atrium hardly plays a key role in comprehending where different kinds of facilities would be across the building.

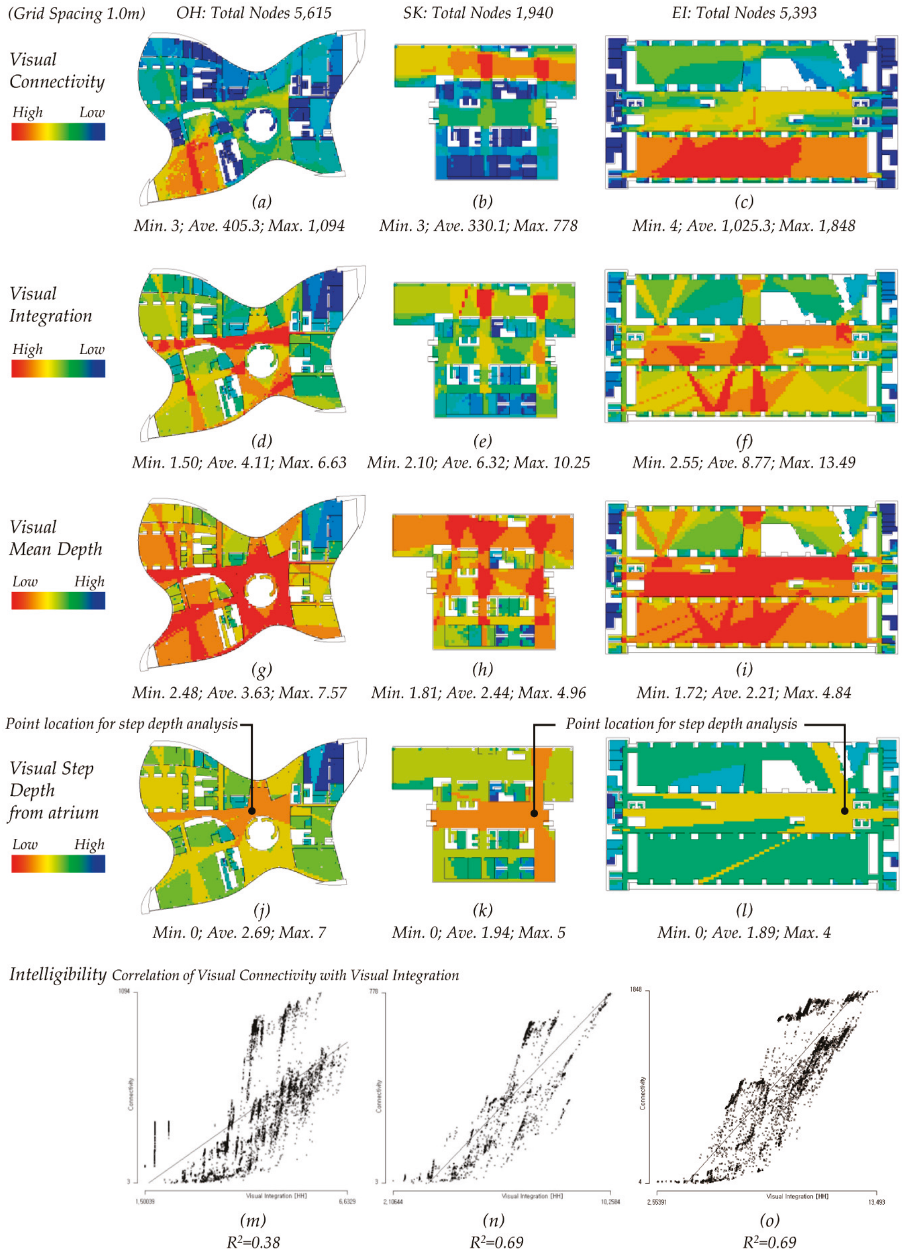


Figure 7. Syntactical results of VGA: (**a**–**c**) visual connectivity; (**d**–**f**) visual integration; (**g**–**i**) visual mean depth; (**j**–**l**) visual step depth from atrium; (**m**–**o**) scattergrams for the intelligibility, which is the correlation between visual connectivity and visual integration with r-squared value.

However, when we look at the visual mean step depth, it is surprising because the atria have the lowest values of total depth (see Figure 7g–i). In other words, the atria decrease the value of total depth. In particular, the SK provides a similar result to those of OH and the EI. For instance, in OH, the low mean depth values, represented in red and close to 2.48, originate from the atrium, the corridors and the conference hall, and the thresholds to the restaurant; in the SK, the low values close to 1.81 are found in the staff lounge and the atrium; and, in the EI, the values are particularly focused in the atrium, and running through the thresholds leading to the lab. In all cases, the atrium plays an important role in reducing the mean depths in total. Like the visual integration analysis, mentioned before, the visual mean depth describes how deep or shallow a certain point location would be in relation to the others at the global level. If a point location has a low mean depth value, it is easy for us to recognize and reach many locations, whereas if it has a high value, it makes it difficult to comprehend where it is and how to get there. Considering this conception, it can be argued that the atrium works well in reducing the mean depths. This, as we have reviewed via the partitioning theory, is because the atrium aims to intentionally remove several partitions, create a single large space horizontally and vertically and connect to adjacent permeable spaces, and, therefore, this is the most economical way of constructing the shortest path from one space to the others within the spatial system.

The visual step depth results make it clear how the atrium reduces the number of step depths (see Figure 7j–l). In OH, for example, most facilities, such as the conference hall, meeting rooms, restaurant, and offices, are placed one step away from the atrium; in the SK, the staff lounge and meeting rooms are directly connected from the point location; in the EI, the lab and the restaurant are easily accessed from the atrium as well.

5.2. Intelligibility (or Understandability)

We can now look at the intelligibility analysis, which is not only an important idea in space syntax but also a useful conception of the morphological features of a building. The graphs in Figure 7m–o show scattergrams for the intelligibility of three cases, and the r-squared values below the graph mean the degree of how intelligible the spatial layout would be in terms of visibility. In this analysis, what we need to look at carefully is OH: the r-squared value is 0.38, and it is quite low, whereas the other two cases show the same intelligibility; that is, 0.69. Why is OH much lower than the others? How can we understand these conflicting results?

This will be answered in terms of partitioning theory. As we reviewed before, this is understood as the theory whereby, as bars are placed at or near the center, extended, continued, and arranged linearly, the total depth of a spatial layout is increased. As a result of the depth gain, the spatial system becomes segregated and unintelligible. In contrast, as they are placed far from the center, shortened, discontinued, and arranged at angles, the total depth is reduced and, as a result, the spatial system becomes integrated and intelligible. From this aspect, it can be argued that the atrium of OH, and specifically the outline of the atrium, acts as a bar; the bar is placed at the center; it is extended, continued, and arranged linearly; it is circled; and, eventually, a block has emerged. As a result, the depth of this spatial layout is higher (the average of visual mean depth: 3.63) than that of the others (SK: 2.44, EI: 2.21) (see Figure 7g–i). Furthermore, the atrium makes it less intelligible (r-squared value of intelligibility: 0.38) than the others (SK: 0.69, EI: 0.69) (see Figure 7m–o).

In syntactical terms, the atrium works as a block, and, indeed, we cannot move through the atrium because of its vertical openness. In reality, however, there are no physically-defined partitions around it. We can see through the atrium, and these particular characteristics enable us to get some useful information about the overall morphological features and how to reach destinations [19]. Even though OH is less intelligible and has greater mean depth compared with the SK and the EI, the atrium of OH still plays an important role in reducing the mean depth across the plan, distributing people to other places, and understanding efficiently the spatial structure.

6. Conclusions and Future Studies

How, then, could we describe sustainable architecture spatially? More specifically, how could we illustrate sustainable architecture syntactically? As we have reviewed before, the three buildings all achieve most of the points assessed by LEED in the USA and CASBEE in Japan, and they are considered the most efficient buildings in the world. They are highly efficient and, therefore, economic, in that they are aimed at minimizing energy consumption by using the most advanced technologies—such as a heat recovery system, LED lighting, triple-layered low-e glass, and a micro-louver system—as well as at maximizing energy creation via a BIPV system, geothermal heat pumps, rainwater harvest, and a light duct system. In particular, the buildings have an atrium at their center for natural ventilation. Considering these advanced technologies and the designed atria, it is certain that economic value is thought of as an important issue in sustainable buildings.

Regarding the economic aspect, Hillier argues that cities can be seen as movement economies, and suggests two principles: one is "natural movement," meaning "the tendency of the structure of the grid itself to be the main influence on the pattern of movement", and the other is "through movement," describing "the by-product of how the grid offers routes from everywhere to everywhere else" [8] (pp. 121–127). From this theory, he stresses that an urban system should be understood as the one which has "at least some origins and destinations more or less everywhere," and, therefore, every trip in an urban system has "three elements: an origin, a destination, and the series of spaces that are passed through on the way from one to the other" [8] (pp. 125–126). In particular, movement in cities occurs on different scales: at a local level, locally integrated spaces are mostly taken at a local scale, whereas globally integrated spaces are mostly used at a global level. What we should note from this economic perspective is the fact that our movement patterns, even within a complex urban system, are results of the movement economies, and therefore, it is obvious that the spatial layout (or formation) is spatially economic.

If we apply this theory and framework to our research question, it can be noted that the economic issue in sustainable architecture does not just mean the design that is achieved by using mostly advanced technologies and minimizing environmentally negative impacts; it also means a highly integrated and understandable design. In other words, it is the architecture wherein a detour movement or disorientation hardly ever occurs. Therefore, it is concluded that sustainable architecture should be seen as an architecture which aims to maximize energy efficiency with the most modern technologies, to minimize the negative impacts on the environment, and, most importantly, to configure spatial patterns and forms in a spatially economical way.

Beside the spatial economics, it might be worth taking a look at whether sustainable architecture has an impact on spatial quality or not. In architecture, spatial quality is one of important issues, such that it might be an additional framework for understanding architecture. However, we could take account of this issue from a social perspective. Without doubt, as Lee argues, atria can be understood as integrated, co-dependent, and comprehensive spaces because they afford a variety of social activities such as resting, standing, waiting, descending or ascending, making one aware of people's movement, and facilitating social behaviors and wayfinding or navigating through the visually vertical and horizontal openness [19]. It means that even though atria are thought of as conceptual spaces, their "combination of bounded convexity and visual openness" promotes social interactions and strengthens virtual community [19] (p. 260). From this social perspective, we can say that sustainable architecture contributes to structuring "a dense and random pattern of encounter", rather than simply a pre-defined social pattern [13], so that it can be said that the objectives of sustainable architecture have an impact on making the spatial quality better.

This study is specifically focused on establishing a theoretical framework for how spatially economically sustainable architecture could be, by using space syntax theory and in particular the partitioning theory and movement economies. However, this approach is deficient in many respects. First of all, this paper has not presented how OH works practically. In other words, it is unclear whether this building works at different scales, how people move around in such an unintelligible building, and whether the atrium would play an important role in distributing people's movement across the entire building. Besides, there is still doubt regarding how the spatial configurations of sustainable buildings would be spatially economic when compared with non-sustainable ones. Therefore, follow-up studies should be carried out to comprehend what sustainable architecture is.

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Sustainable Design Alternatives and Energy Efficiency for Public Rental Housing in Korea

So-Young Lee and Myoung-Won Oh *

Department of Housing and Interior Design, Chung-Ang University, Seoul 06911, Korea; soyo@cau.ac.kr
* Correspondence: annaoh@cau.ac.kr; Tel.: +82-31-670-4788; Fax: +82-31-676-7599

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Abstract: The orientation and shape of a building can influence energy efficiency in both heating and cooling mechanisms. Given the climatic conditions of Korea, many people are concerned about housing orientation and prefer south-oriented locations. As such, many housing complexes consist of a series of long narrow units that are south-facing. The purpose of this study is to investigate design alternatives for the layout of a building complex, size of households, width to depth ratios of floorplans, and design and type of façade; to examine energy efficiency using energy simulation programs; and to suggest diverse design alternatives for public rental housing, as well as energy-efficient options. The alternative housing units, which are more square-shaped than the typical long and rectangular type, resulted in higher energy costs. Simulation results show that as the solar radiation load increases or the window area increases due to plan alteration, there is simultaneously a significant increase and decrease in the cooling and heating loads, respectively. The performance of the suggested layout alteration greatly increased the heating load and slightly decreased the cooling load with similar total energy costs.

Keywords: sustainable design; energy efficiency; public rental housing; social housing; building simulation

1. Introduction

Building sectors were responsible for 28% of global energy-related CO_2 emissions in 2019 [1], while heating, ventilation, and air-conditioning systems accounted for 37% of the total energy consumption in buildings. In Korea, of the total energy produced, approximately 20% was consumed in buildings, half of which was consumed in residential buildings [2]. Energy consumption is one of the crucial areas of concern in terms of sustainability [3]. For low-income families, energy-efficient housing lead to significant savings, and integrated green strategies increase housing affordability [4], especially in terms of space, heating, cooling, and lighting.

To improve energy efficiency, it is emphasized to find optimal solutions for heating and cooling loads in the early stage of design [5]. Architectural design features such as building orientation, shape, façade, and its envelope are found to have significant influence on energy loads and their trade-offs [6–8]. Many existing studies have explored more efficient ways to link architectural design features and engineering systems with energy consumption [9,10].

For sustainable application, it is especially necessary to consider not only universal principles such as development without compromising future needs but also unique contexts such as the climate and locality. In the residential sector, it is important to consider local climate as well as demographic changes when exploring design alternatives for efficient energy consumption.

Since Korea has four distinct seasons with severe temperature gaps from −7 °C to 30 °C, extremely hot and humid in summer and extremely cold and dry in winter, there is a strong tendency to prefer south-oriented housing under this climate and culture [11]. Considering these extreme variations in temperature, cooling load needs to be taken into account in addition to heating load.

Previous studies have identified the different factors that affect energy consumption in buildings and have investigated how to improve energy efficiency and decrease costs of energy by manipulating these factors. To increase energy efficiency, some architectural design features, namely (1) building orientation; (2) building envelope; (3) plan shape and complexity; (4) story and height; (5) windows and glazing; (6) floor spans; and (7) circulation space, were suggested [5]. In another study, to reduce the demand for energy in residential buildings, building design criteria included a building envelope system, glazing, shading, orientation, shape, and passive heating and cooling mechanisms [7]. Abanda and Byers [12] estimated energy saving costs throughout the lifetime of simulated cases of a well-orientated domestic building using Building Information Modeling (BIM) tools, Revit and Green Building Studio. Among these factors, many studies consistently found that building orientation is a critical factor for improving energy efficiency in buildings [6,7,13].

Besides building orientation, the shape and size of a building can influence energy consumption. A compact shape, such as an orthogonal building, is desirable in minimizing the cost of energy but not desirable for daylight use. An additional advantage is that a compact shape minimizes heat loss by 6–10% [14]. Aksoy and Inalli [8] found that the rates of saving heating energy vary from 34% to 36% depending on the orientation and different shapes of buildings, including other shape factors. They concluded that buildings with a square shape have more advantages, and the most suitable building orientation angles were 0 and 80, in a building with a ratio of length to depth of 2/1 and 1/2, respectively.

Halawa et al. [9] emphasized that façades play an important role in the overall energy consumption in a building and represent the physical appearance of buildings. They suggested a holistic approach in considering façade design options, including façade aesthetics, to attain sustainable buildings. Mirrahimi et al. [15] identified the energy impact variables for designing building façades. They include building physics, building location, external/internal walls and materials, thermal insulation, windows, glazing, window-to-wall ratio, and external shading. Building physics refers to the shape elements of a building such as the form, height, length, and width. Since building façade designs include windows, shading devices and materials significantly influence energy performance in terms of heating, cooling, ventilation, and lighting [16]. Energy efficiency that is influenced by building orientation is related to the façade features of a building.

Using BIM, energy performance was evaluated by changing the following factors: the geometric shape of buildings (ratio of long side to short side), floor area, volume, window area ratio, orientation of the building, and total surface area (envelope area) of the building for residential and office facilities. In residential buildings, the building envelope influenced energy consumption by 42.5%, whereas it only influenced office buildings by 17.1% [10]. These studies identified each important architectural design element for energy consumption and determined how influential each variable was for heating, cooling, and daylighting, or as a part of total energy performance. Some studies investigated more than two variables and their impacts on energy consumption. Nevertheless, investigations and energy consumption simulations that explore the variables which can influence heating and cooling loads simultaneously, as well as total energy saving from the occupant's perspective, are lacking. A few studies have examined the integrative impact of a wide range of building design factors on energy consumption. Even still, this integrative approach considered various factors and emphasized energy optimization processes for each project through energy simulation or using the BIM tool, rather than exploring generalized design applications for energy efficiency [17,18].

Some studies incorporating predictive models with configurations of simulated conditions have proposed a case for the final design or provided methods to achieve nearly Zero-Energy Buildings (nZEB) for residential purposes. Globally, many urban environments are facing population growth, and the demand for residential buildings, including affordable housing, has increased. Residential buildings account for a major part of the energy consumption in the building sector [19]. In addition, with regard to affordable housing, a sustainable and energy-efficient building is important in terms of the cost of lifelong housing. However, there is a lack of systematic analyses and evidence on the costs of construction and price estimation for lifelong green affordable housing; people presume that green, sustainable buildings are expensive to build [20].

With a developer of a multi-family sustainable housing community in the USA, Cheng et al. [18] indicate that the energy performance of multi-family buildings has not been thoroughly examined to include interactive effects of different variables; instead, the effect of each building and architectural variables on energy efficiency have been analyzed individually. They proposed two scenarios for assessing ten building variables that seem to have an influence on energy consumption. This approach is helpful in identifying design trade-offs in the early stage of a design process and in determining a final energy-efficient design of sustainable housing. Although the results were hard to generalize, this approach showed the interactive effects of energy variable adjustments in the plan and configuration of a building and design optimization processes for energy efficiency.

In addition, some studies reveal that highly energy-efficient buildings can decrease primary energy consumption by 90% in the Mediterranean area [21]. The concept of nZEB has been introduced and implemented worldwide, and the EU (Energy Performance of Buildings Directive) requires all new buildings to be nearly zero-energy by the end of 2020 [22]. In Korea, net zero-energy buildings in a residential community (121 house units), as a best practice, were also initiated and built by the government in 2017. Building materials and construction techniques can improve energy efficiency; however, still, in general, the majority of housings have a similar shape, since regarding the site plan and housing building, the south orientation is traditionally critical in capturing solar heat in Korea. In some super-high-rise apartments in Korea, universal techniques have been widely applied and the internal space of buildings has become sealed and separated from the external space, which is in contrast to the sustainable design strategy [23].

Due to rapid urbanization and an increase in population, apartments have become the most popular type of housing in cities as a result of mass supply, and more than 50% of people in Korea live in apartments [24]. An apartment as a major type of housing, represented in the shape of a simple concrete box as an outcome of economic development, has become common regardless of households and location. Regarding housing for those with low income, public rental apartments are a form of affordable or social housing in Korea and are more notorious for their homogeneous unit plan and building shape. Most public rental housing in Korea is characterized by its small size, narrow rectangular shape of units, narrow balcony, and long corridors due to size limitations, and most housing complexes consist of a series of long narrow units aligned to face south [25]. This is partially due to the fact that, traditionally, more housing units need to face south, and each house unit has smaller south-facing areas along the site. The linear south-facing housing building complexes are parallel to each other and are aligned. The ratio of housing units is far from representing a square shape, and it does not support the changing needs and lifestyles of the occupants. According to the Korea Housing Survey in 2017, the demand for rental housing among young adults living alone was extremely high, with lease occupancy accounting for 53.8% in the different types of housing occupancy [24]. Since public rental housings in Korea are extremely monotonous, and typical housing units are stereotyped, as it seems, they neither support the changing needs of occupants nor improve energy efficiency. Furthermore, considering the longitude of the Korean Peninsula, the climatic conditions have changed dramatically as the amount of energy loads for cooling has increased compared to the conventional amount of energy demand for heating [26]. It is necessary to investigate design alternatives with differently shaped housing units to meet growing demands for diverse housing and changing housing requirements—for example, exploring more south-facing square housing units or sacrificing southern orientation by incorporating different layouts for each housing unit. Nowadays, public agencies and the government are putting forth efforts to provide various design alternatives [27] while minimizing housing fees that occur as a result of an increase in energy performance in response to growing and changing demands.

Therefore, the purpose of this study is to investigate design alternatives for the layout of building complexes, size of households, width to depth ratios of floorplans, and type and design of facade and to examine energy efficiency using energy simulation programs from Integrated Environmental

Solutions (IES), Virtual Environment (VE) 2017 in order to suggest diverse design alternatives for public rental housing as well as energy-efficient options.

2. Materials and Methods

2.1. Base Model and Design Alternatives

To simulate energy performance according to various designs of public rental apartments, it is necessary to establish a base model and design alternatives. To this end, the characteristics of the floor plan of small public rental apartments in Korea, the layout and orientation of units, and the design of the elevation were investigated. The base models and design alternatives were set up by reflecting on these factors. The base model, which has a size and unit type that is typical of Korean rental housing, was set at 39 square meters with a rectangular shape; the units of the base model are arranged linearly and are south-facing.

2.2. Energy Simulation

To examine the energy efficiency of design alternatives, energy simulation was conducted using VE 2017 (https://www.iesve.com/ve2017). For the simulation, weather condition data were based on the Seoul meteorological data of the Solar Energy Society. The thermal insulation conditions of the building (U-value) were based on the energy saving design standards of buildings in 2017. For the internal heating conditions and schedules, in terms of residential living conditions, it is assumed that there are 2 persons per household. The conditions for the computer simulation of the base model energy performance were verified by comparing the heating costs with the heating costs of 10 apartments that have the same heating system and size. Further, for the results of energy efficiency, the cost of cooling and heating of the ten households on a typical floor were estimated, and each cost was compared according to design alternatives.

2.2.1. Conditions for Simulation

- Internal heat source condition and schedule: They were set based on ASHRAE 90.1 (Energy Standard for Buildings) and power consumption per Korean household (see Table 1).

Table 1. Internal heat source condition and schedule.

	Density	Schedule	Remark
Lighting	6.45 W/m^2	ASHRAE 90.1	ASHRAE 90.1
Use of equipment	10.97 W/m^2	ASHRAE 90.1	Excluding the energy consumption of lighting *
Persons	2 persons/household	ASHRAE 90.1	Sensible heat 73.27 W/person, Latent heat 58.61 W/person

* Electricity consumption for 2 persons/household is 212.3 kWh/month (according to statistics from the 2015 edition of the Organization for Economic Cooperation and International Energy), while monthly electricity consumption per person is 106.2 kWh/month. Here, lighting power and energy consumption are excluded.

- Infiltration (including natural ventilation): 0.65 air change per hour (ACH). According to a study that measured the amount of infiltration and natural ventilation in Korean residential spaces, it is 0.6 ACH~0.7 ACH [23]. Therefore, the amount of infiltration and natural ventilation was set to 0.65 ACH in the simulation.
- Heating and cooling system: For cooling efficiency, the minimum standard of efficiency of the Efficiency Management Equipment Operation Regulation (29 December 2017) was applied. The heating efficiency was assumed to be applied to 100% of the heat measured in the household (see Table 2) because heating costs are calculated from the amount of heating heat supplied to households in the case of district heating. The indoor setting temperature was 26 degrees in summer and 21.7 degrees in winter. The operating time of the heating and cooling system was set to 24 h.

Table 2. Heating and cooling system.

	System	Efficiency	Set Temperature	Operating Time
Cooling	Air conditioner	COP 3.50	26.0	24 h
Heating	District heating	100%	21.7	24 h

- Electricity and district heating calculation conditions (see Table 3):

Table 3. Electricity and district heating calculation conditions.

	Heat Source	Unit Price		Remark
Cooling	Electricity	0–200 (kWh)	187.9 (Won/kWh)	Besides the 212.3 kWh consumption per household, it was assumed that there was additional consumption from air conditioning.
		more than 200 (kWh)	280.6 (Won/kWh)	
Heating	Hot water	64.35 (won/Mcal) 55.33 (won/kWh)		Korea District Heating Corporation heat rate table (1 November 2017 part)

2.2.2. Validation of the Conditions for the Simulation

The reliability of conditions for the simulation was verified by comparing the costs of heating in the simulation model with the costs of heating 39 m^2 apartments in the Seoul area. To verify the conditions assumed for the simulation, the output values (energy costs) were compared with the actual cost reported by the apartment housing management information system operated by the Ministry of Land, Infrastructure and Transport and the Korea Appraisal Board (the 10 cases were chosen from the open data source which includes energy costs from housing units with the same size of unit (39 m^2), the same type of public rental apartment built more than 10 years ago, located in Seoul metropolitan region). The estimated energy costs were within the range of actual costs and close to the mean value of 10 cases.

- The costs of heating in the 39 m^2 apartments in the Seoul area: As a result of a survey of ten apartment complexes with an exclusive area of 39 m^2 in Seoul, annual costs of heating were estimated to be 187,885 won (see Table 4).

Table 4. The cost of heating of a 39 m^2 household in Seoul area.

	Built Year	Area (m^2)	Heat Source	Annual Heating Cost (won/year)
1	2009	38.7	district heating	217,368
2	1992	38.6	district heating	131,340
3	1994	40.0	district heating	257,208
4	1994	39.6	district heating	177,108
5	1995	39.6	district heating	192,660
6	1992	39.6	district heating	185,328
7	1991	40.0	district heating	229,644
8	1998	39.7	district heating	242,928
9	1990	39.9	district heating	99,684
10	1987	38.0	district heating	145,584
Mean				187,885

Sources: Apartment housing management information system is operated by the Ministry of Land, Infrastructure, and Transport together with the Korea Appraisal Board (http://www.k-apt.go.kr/).

- Comparison with the simulation model: The annual cost of heating of the simulation model is estimated at 194,316 won. It was considered that the difference from the survey value was 3.4%, and the current condition of the simulation was considered to be valid (see Table 5). Most of the complexes were completed before the year 2000, and the insulation standards of the rules on facility standards, and so forth, of buildings (enforcement on 1 June 1992) were applied and reviewed.

Table 5. The cost of heating of a 39 m^2 household in Seoul area.

	Annual Heating Cost	Difference
Survey value	187,885 won/yr	
Simulation model value	194,316 won/yr	3.4%

3. Base Model and Design Alternatives

In this study, we aimed to examine changes in energy performance between various designs of small rental apartments. The most typical small rental apartment model in Korea was investigated and set as the base model. In addition, various design attempts that have been recently implemented were investigated in terms of their changes to plan shape, layouts between units, the orientation of units, and elevation. Based on this analysis, design alternatives were derived.

The LH (Korea Land & Housing Corporation) Research Report (2012) analyzed the floor plan of an existing LH rental apartment and presented the 2011 LH standard plan. Later, in 2014, LH developed LH's customized floor plan, which was the design of a floor plan for a rental apartment tailored to consumers, and proposed the plan of 1Bay_Studio for 16 m^2, 2Bay_1Bed for 36 m^2, and 2Bay_2Bed for 46 m^2 [28]. The floor plan of the rental housing (Nowon Energy Zero Housing) in Nowon-gu, Seoul, built in 2018, was developed as 2Bay_2Bed for 39 m^2 and 2Bay_3Bed for 49 m^2. The floor plan for the unit with an area of 39 m^2 remarkably included the types of 1Bay_1Bed, 2Bay_1Bed, and 2Bay_2Bed unit sizes for the design characteristics of small apartments under 50 m^2, categorized the shape of the unit plan by measuring the length of the long side, the length of the short side, and the area of the units [29] (see Table 6). In the past, units with an area of 30–40 m^2 were typically "1Bay_Studio" or "1Bay_1Bed", arranged in a row along the corridor. Recently, as various designs of rental apartments have been attempted, a "2Bay-1Bed" plan emerged. A 39 m^2 "2Bay_2Bed" type can also be found. Therefore, the target area for the simulation was set to 39 m^2, with many changes made to the shape of the plan. The total area of a housing unit is not gross area; it excludes a space used for public common use, an electrical or mechanical drill, and a balcony space.

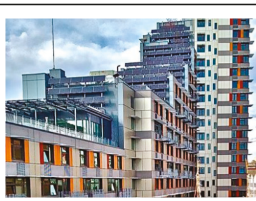
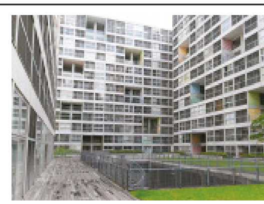
Table 6. Small floor plans of less than 50 m^2.

Object (Year)	Type	Floor Plan	Characteristics of Shape	
2011 LH standard plan (2011)	1Bay_1-Bed		Area (m^2)	39
			Short side (mm)	5000
			Long side (mm)	9000
LH's customized floor plan (2014)	2Bay_1-Bed		Area (m^2)	36
			Short side (mm)	6100
			Long side (mm)	6700
Nowon Energy Zero Housing (2018)	2Bay_2-Bed		Area (m^2)	39
			Short side (mm)	6500
			Long side (mm)	7500

- The floor plan of the base model and alternative design: The floor plan of the base model used in the simulation is the "1Bay_1-Bed" type, which is the most common in rental housing, and the area is 39 m^2, the short side is 5000 mm, and the long side is set at 9000 mm. An alternative design in the plan "Plan_alt1" is a "2Bay_1-Bed" type that has recently begun to appear at 39 m^2, which is the same as the area of the base model. The short side is 6500 mm and the long side is 7000 mm. The area used for the simulation is based on the area of exclusive use and an indoor space (excluding spaces for public use, such as an electrical or mechanical facility space or a balcony space).
- The layout of the base model and alternative design: Units in Korean rental apartments that were built in the past are mostly arranged in a row along the corridor. In some cases, units that face each other around the corridor can be found. There is also a core-centered layout called "tower type." The layout of the base model is a typical long and narrow corridor-type with a single row arrangement. The design alternatives for the layout were "Layout_alt1", which is arranged in two rows facing the corridor, and "Layout_alt2", which is a tower type.
- The orientation of the base model and alternative design: In Korea, where there are four seasons, south-facing is the preferred arrangement of units. However, there are many cases where it is difficult to place all units in this way. As the next best thing, southwest- or southeast-facing units are often mixed into the design. In order to examine energy performance according to orientation, the base model was set to south-facing, "orientation_alt1" when combined with southeast, and "orientation_alt2" when combined with southwest.

Most rental apartments in Korea have flat elevation designs. However, in other countries, it is easy to find various elevation designs, even in rental housing [27]. Recently, in Korea, various elevation designs have been attempted to improve the image of rental apartments. Table 7 shows examples of various elevation designs for rental housing. Among them, Sejong City's LH's Tomorrow City is a representative example of several units protruding forward or the absence of units in the middle. This not only affects the exterior design but also creates a variety of interior spaces and a flexible space, and this can affect energy performance. The protruding units may act as an awning for other units, or the energy performance may deteriorate due to the increase in the exterior walls in the open space. Therefore, an alternative to the elevation design, "Elevation_alt1", was set in the form of an empty unit in the middle.

Table 7. Various designs of the elevation of rental housing.

		
VIA-VERDE (New York, NY, USA)	HONEYCOMB (Livade, Slovenia)	Codan block 1 (Tokyo, Japan)
		
Tomorrow City (Sejong, Korea)	Tomorrow City (Sejong, Korea)	EZ house (Seoul, Korea)

4. Energy Performance for Design Elements

We simulated the energy performance for housing alternatives by changing the shape of units (proportion), layout, and orientation and examined the effects of design options of the alternatives on energy performance.

Some of the design alternatives and diverse house unit compositions have been developed based on a previously conducted case analysis. The targeted housing complex case is situated in Seoul and Kyung-gi province, in the middle of the Korean Peninsula. Design variables affect several building features including ambient features such as daylight penetration, airflow, energy loss or efficiency, and aesthetic appraisal. Among these factors, for public rental housing, energy issues are crucial since most of the residents of public rental housing are in the low income or more socially vulnerable class, and they are more concerned about housing fees, including the cost of energy.

4.1. Characteristics of Energy Consumption of the Base Model

Ten households arranged in a row on the reference floor were analyzed (see Figure 1), and annual heating and cooling load, as well as the characteristics of energy consumption, were analyzed as average values (see Section 2.2, Energy Simulation, for an explanation of simulation conditions, and Section 3, Base Model and Design Alternatives, for an explanation on the simulation targets). Annual heating load and annual cooling load were calculated as heat gain and heat loss for each load generation period. Heat gain was calculated by dividing the lighting used indoors, various types of equipment (including electronic devices), occupants, and solar radiation heat. Heat loss was calculated by splitting it into groups of "exterior walls" for walls facing the outside air, "windows" for windows and doors, "interior walls" for walls not facing the outside air, and "infiltration" for ventilation and infiltration (refer to Appendix A for the thermal transmittance of the building used in the simulation).

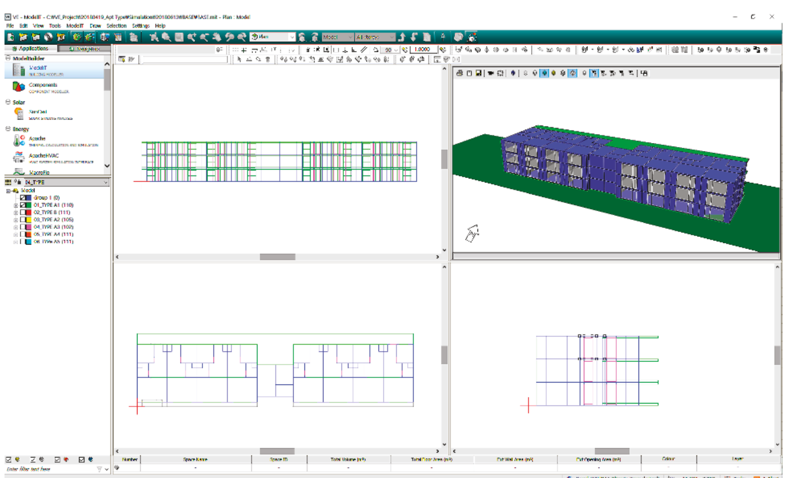


Figure 1. Modeling of base model.

4.1.1. Heating and Cooling Load

- Annual heating load: The biggest factor influencing heat loss was infiltration, followed by windows and exterior walls, and the biggest factor influencing a reduction in the annual heating load was solar radiation (see Table 8).
- Annual cooling load: The biggest factor influencing heat acquisition was solar radiation, followed by equipment, and the biggest factor influencing heat loss was infiltration (see Table 9).

Table 8. Heating load of base model.

	Heat Gain					Heat Loss					Etc.	Annual Heating Load
	Lighting	Equipment	Persons	Solar Radiation	Total	Exterior Walls	Windows	Interior Walls	Infiltration	Total		
Base model (kWh)	36.1	612	305	821	2099	−578	−696	−499	−1620	−3393	165	1129
Ratio (%)	17.2	29.2	14.5	39.1	100.0	17.0	20.5	14.7	47.8	100.0	–	–

Etc. is a value that corrects errors caused by heat storage.

Table 9. Cooling load of base model.

	Heat Gain (kWh)					Heat Loss (kWh)					Etc.	Annual Cooling Load
	Lighting	Equipment	Persons	Solar Radiation	Total	Exterior Walls	Windows	Interior Walls	Infiltration	Total		
Base model (kWh)	511	867	777	1574	3728	−219	−321	−174	−648	−1362	−5	2361
Ratio (%)	13.7	23.3	20.8	42.2	100.0	16.0	23.6	12.8	47.6	100.0	–	-

Etc. is a value that corrects errors caused by heat storage.

4.1.2. Annual Energy Consumption and the Costs of Heating and Cooling

For heating, the efficiency value is 100%, so the annual heating load is equal to the annual energy consumption (see Table 2). For cooling, the annual energy consumption for the annual cooling load is calculated using the efficiency, COP3.5. According to electricity and district heating calculation conditions (see Tables 2 and 3), for heating and cooling, the amount of energy consumption is the amount of heating/cooling load divided by efficiency value. The annual cost of heating is estimated at 62,445 won, and the cost of cooling is 133,517 won. Therefore, the combined annual cost of cooling and heating is 195,962 won (see Table 10).

Table 10. Annual costs of heating and cooling of base model.

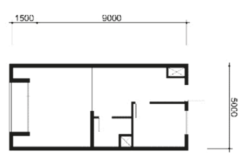
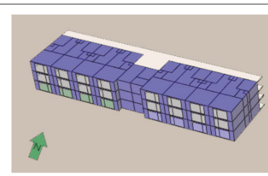
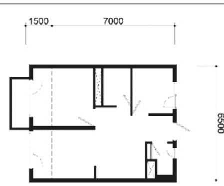
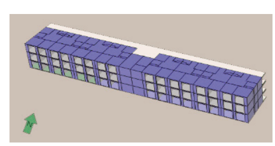
Heating Cost				Cooling Cost				Total
Annual Heating Load (kWh)	Efficiency (%)	Energy Consumption (kWh)	Annual Heating Cost (won)	Annual Cooling Load (kWh)	Efficiency (COP)	Energy Consumption (kWh)	Annual Cooling Cost (won)	(won)
1129	100	1129	62,445	2361	3.5	674.5	133,517	195,962

4.2. Comparison of Base Model and Alternative Design

4.2.1. The Alternative Design According to the Shape of the Floor Plan of Units

The width and length of the basic unit is 5000 × 9000 mm, and that of the alternative design unit is 6500 × 7000 mm, which is an increase in the width and a decrease in the length. Compared to the base model, in the alternative model, occupants have more living space as a result of reducing circulation areas (see Table 11).

Table 11. Floor plan of base model and alternative design.

Type	Shape of the Plan	Shape of the Elevation
Base		
Plan_alt1		

- Comparison of heating load

Solar radiation increased according to the change in shape of the horizontal and vertical plan, and heat gain in terms of solar radiation increased. The change in the shape of the floor plan brought about a change in the window area, and there was an increase in heat loss in proportion to the windows. Therefore, the overall heating load was found to be slightly reduced (see Table 12).

- Comparison of cooling load

Increased solar radiation and increased window area led to an increase in the cooling load (see Table 13).

- Comparison of annual costs of heating and cooling

Annual heating costs and annual cooling costs are incurred by units that have both many walls facing the outside air and few walls facing the outside air. Therefore, "Mean" (the average value of each unit) was compared, and "Deviation" (the deviation from the average value) was analyzed.

The average annual cost of heating for households decreased by 4.8%, and the annual cost of cooling increased by 18.5%, and the annual combined costs of cooling and heating increased by 11.1%. The deviation in costs of heating between households was −21.2%, and the deviation in costs of cooling was −3.6%, which was less than the costs of heating (see Table 14 and Figure 2).

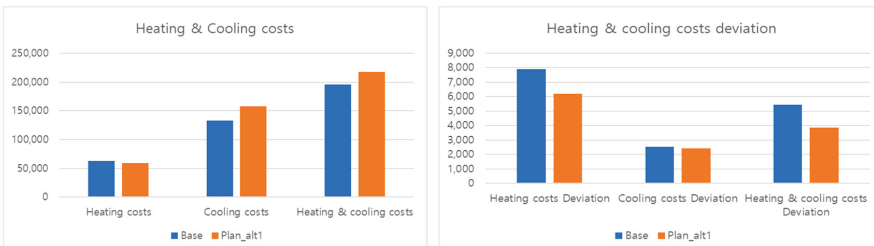


Figure 2. Costs of heating and cooling of plan_alt1.

4.2.2. The Alternative Design According to the Layout of Units

The layout of the basic unit is a linear type, "Layout_alt1" is a parallel type, and "Layout_alt2" is a mixed type (see Table 15).

Table 12. Heating load of plan_alt1.

	Heat Gain					Heat Loss					Etc.	Annual Heating Load
	Lighting	Equipment	Persons	Solar Radiation	Total	Exterior Walls	Windows	Interior Walls	Infiltration	Total		
Base (kWh)	361	612	305	821	2099	−578	−696	−499	−1620	−3393	165	1129
Plan_alt1 (kWh)	361	612	305	1103	2380	−544	−942	−467	−1638	−3591	137	1074
Rate of change (%)	0.0	0.0	0.0	34.3	13.4	−5.8	35.4	−6.4	1.1	5.8		−4.8

Etc. is a value that corrects errors caused by heat storage.

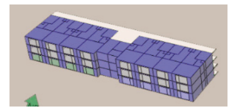
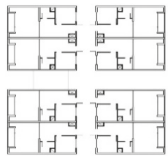
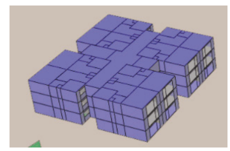
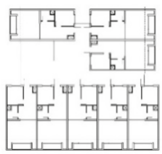
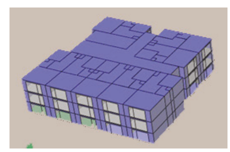
Table 13. Cooling load of plan_alt1.

	Heat Gain (kWh)					Heat Loss (kWh)					Etc.	Annual Cooling Load
	Lighting	Equipment	Persons	Solar Radiation	Total	Exterior Walls	Windows	Interior Walls	Infiltration	Total		
Base (kWh)	511	867	777	1574	3728	−219	−321	−174	−648	−1362	−5	2361
Plan_alt1 (kWh)	511	867	777	2090	4245	−207	−434	−157	−653	−1451	4	2798
Rate of change (%)	0.0	0.0	0.0	32.8	13.9	−5.3	35.1	−9.5	0.6	6.5		18.5

Table 14. Costs of heating and cooling of plan_alt1.

	Heating Costs				**Cooling Costs**				**Heating and Cooling Costs**			
	Min.	**Max.**	**Mean**	**Deviation**	**Min.**	**Max.**	**Mean**	**Deviation**	**Min.**	**Max.**	**Mean**	**Deviation**
Base (won)	54,539	72,089	62,445	7891	129,919	135,940	133,517	2522	190,479	202,008	195,963	5433
Plan_alt1 (won)	53,233	67,337	59,438	6219	154,532	160,486	158,196	2431	213,707	221,983	217,634	3862
Rate of change (%)	−2.4	−6.6	−4.8	−21.2	18.9	18.1	18.5	−3.6	12.2	9.9	11.1	−28.9

Table 15. Layouts of base model and alternative design.

Type	Shape of the Plan	Shape of the Elevation
Base		
Layout_alt1		
Layout_alt2		

- Comparison of heating load

According to the change in layout, heat gain through solar radiation decreased, and heat loss through the interior walls increased. Therefore, it was found that according to the layout, there was a large difference in heating load (see Table 16).

- Comparison of cooling load

According to the change in layout, there was a noticeable difference between heat gain due to solar radiation and heat loss due to the interior walls, and it was predicted that the cooling load decreased (see Table 17).

- Comparison of annual costs of heating and cooling

The average annual cost of heating for households increased by 31.9% (layout_alt1) and 21.1% (layout_alt2), and the annual cost of cooling decreased by 16.1% (layout_alt1) and 10.5% (layout_alt2), and the combined annual costs of cooling and heating increased by 0.8% (layout_alt1) and 0.4% (layout_alt2). There was a large deviation in the costs of heating and cooling between households (see Table 18 and Figure 3). This result implies that households in the alternative apartment complex have extremely different costs of energy.

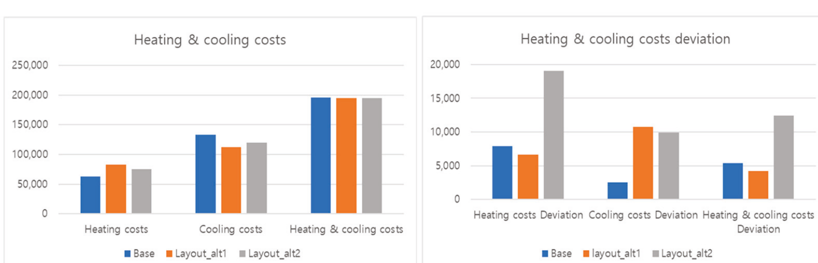


Figure 3. Costs of heating and cooling of layout_alt1 and layout_alt2.

Table 16. Heating load of layout_alt1 and layout_alt2.

		Heat Gain					Heat Loss					Etc.	Annual Heating Load
		Lighting	Equipment	Persons	Solar Radiation	Total	Exterior Walls	Windows	Interior Walls	Infiltration	Total		
Base (kWh)		361	612	305	821	2099	−578	−696	−499	−1620	−3393	165	1129
Layout _alt1	Value (kWh)	361	612	305	521	1798	−294	−620	−1216	−1597	−3727	440	1489
	Rate of change (%)	0.0	0.0	0.0	−36.6	−14.3	−49.0	−10.9	143.5	−1.4	9.9		31.9
Layout _alt2	Value (kWh)	361	612	305	676	1954	−242	−622	−1296	−1607	−3767	446	1367
	Rate of change (%)	0.0	0.0	0.0	−17.6	−6.9	−58.1	−10.6	159.6	−0.8	11.0		21.1

Table 17. Cooling load of layout_alt1 and layout_alt2.

		Heat Gain					Heat Loss					Etc.	Annual Cooling Load
		Lighting	Equipment	Persons	Solar Radiation	Total	Exterior Walls	Windows	Interior Walls	Infiltration	Total		
Base (kWh)		511	867	777	1574	3728	−219	−321	−174	−648	−1362	−5	2361
Layout _alt1	Value (kWh)	511	867	777	1355	3509	−106	−283	−444	−629	−1462	11	2058
	Rate of change (%)	0	0	0	−13.9	−5.9	−51.5	−12.0	155.4	−3.0	7.3		−12.9
Layout _alt2	Value (kWh)	511	867	777	1411	3566	−87	−284	−452	−636	−1459	7	2114
	Rate of change (%)	0	0	0	−10.3	−4.4	−60.1	−11.7	159.9	−1.9	7.1		−10.5

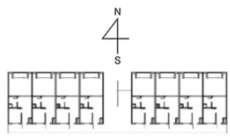
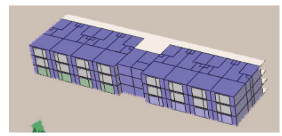
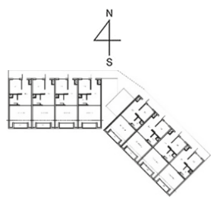
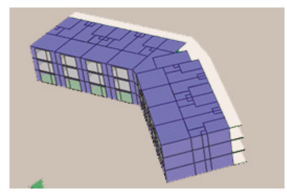
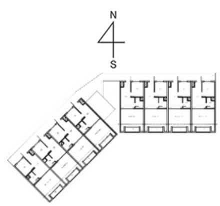
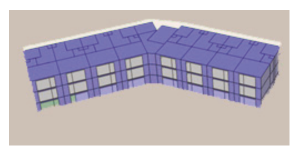
Table 18. Costs of heating and cooling of layout_alt1 and layout_alt2.

		Heating Costs				Cooling Costs				Heating and Cooling Costs			
		Min.	**Max.**	**Mean**	**Deviation**	**Min.**	**Max.**	**Mean**	**Deviation**	**Min.**	**Max.**	**Mean**	**Deviation**
Base (won)		54,539	72,089	62,445	7891	129,919	135,940	133,517	2522	190,479	202,008	195,963	5433
Layout _alt1	Value (won)	74,812	90,182	82,388	6685	100,991	124,490	112,003	10,787	188,805	199,302	194,391	4255
	Rate of change (%)	37.2	25.1	31.9	−15.3	−22.3	−8.4	−16.1	327.8	−0.9	−1.3	−0.8	−21.7
Layout _alt2	Value (won)	61,018	116,835	75,609	19,046	103,711	131,146	119,542	9883	181,820	220,744	195,151	12,402
	Rate of change (%)	11.9	62.1	21.1	141.4	−20.2	−3.5	−10.5	291.9	−4.5	9.3	−0.4	128.3

4.2.3. The Alternative Design According to the Orientation

The orientation of "orientation_alt1" is southeast and the orientation of "orientation _alt2" is southwest (see Table 19).

Table 19. Direction of base model and alternative design.

Type	Shape of the Plan	Shape of the Elevation
Base		
Orientation_alt1		
Orientation_alt2		

- Comparison of heating load

The change in heating load was not large considering the change in the southeast or southwest orientation (see Table 20).

- Comparison of cooling load

The change in cooling load was not large considering the change in the southeast or southwest orientation (see Table 21).

- Comparison of annual costs of heating and cooling

The change in annual costs of heating and cooling was not large considering the change in the southeast or southwest orientation.

There is a significant increase in the deviations of heating and cooling; however, the total deviation of energy consumption in terms of heating and cooling is similar to that of the base model (see Table 22 and Figure 4).

Table 20. Heating load of direction_alt1 and direction_alt2.

		Heat Gain					Heat Loss					Etc.	Annual Heating Load
		Lighting	**Equipment**	**Persons**	**Solar Radiation**	**Total**	**Exterior Walls**	**Windows**	**Interior Walls**	**Infiltration**	**Total**		
Base (kWh)		361	612	305	821	2099	−578	−696	−499	−1620	−3393	165	1129
Orientation _alt1	Value (kWh)	361	612	305	778	2055	−544	−694	−661	−1615	−3514	264	1195
	Rate of change (%)	0.0	0.0	0.0	−5.3	−2.1	−5.8	−0.3	32.4	−0.3	3.6		5.9
Orientation _alt2	Value (kWh)	361	612	305	761	2039	−544	−693	−658	−1614	−3509	262	1208
	Rate of change (%)	0.0	0.0	0.0	−7.3	−2.9	−5.9	−0.4	31.9	−0.4	3.4		7.0

Table 21. Cooling load of direction_alt1 and direction_alt2.

		Heat Gain					Heat Loss					Etc.	Annual Cooling Load
		Lighting	**Equipment**	**Persons**	**Solar Radiation**	**Total**	**Exterior Walls**	**Windows**	**Interior Walls**	**Infiltration**	**Total**		
Base (kWh)		511	867	777	1574	3728	−219	−321	−174	−648	−1362	−5	2361
Orientation _alt1	Value (kWh)	511	867	777	1588	3742	−204	−319	−272	−643	−1439	−3	2300
	Rate of change (%)	0	0	0	0.9	0.4	−6.5	−0.6	56.6	−0.8	5.7		−2.6
Orientation _alt2	Value (kWh)	511	867	777	1557	3712	−204	−319	−271	−643	−1436	−2	2274
	Rate of change (%)	0	0	0	−1.0	−0.4	−6.8	−0.8	55.7	−0.9	5.4		−3.7

Table 22. Costs of heating and cooling of direction_alt1 and direction_alt2.

		Heating Costs				Cooling Costs				Heating and Cooling Costs			
		Min.	**Max.**	**Mean**	**Deviation**	**Min.**	**Max.**	**Mean**	**Deviation**	**Min.**	**Max.**	**Mean**	**Deviation**
Base (won)		54,539	72,089	62,445	7891	129,919	135,940	133,517	2522	190,479	202,008	195,963	5433
Orientation _alt1	Value (won)	54,616	82,082	66,122	10,391	113,063	137,597	130,027	9161	189,880	206,580	196,149	5068
	Rate of change (%)	0.1	13.9	5.9	31.7	−13.0	1.2	−2.6	263.3	−0.3	2.3	0.1	−6.7
Orientation _alt2	Value (won)	54,594	87,095	66,833	10,858	112,616	135,799	128,591	9043	189,777	205,033	195,424	5355
	Rate of change (%)	0.1	20.8	7.0	37.6	−13.3	−0.1	−3.7	258.6	−0.4	1.5	−0.3	−1.4

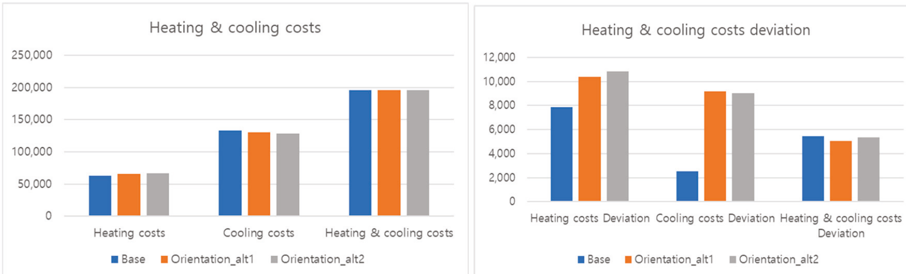
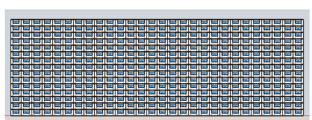
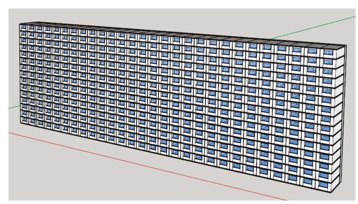
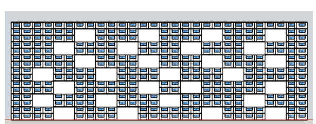
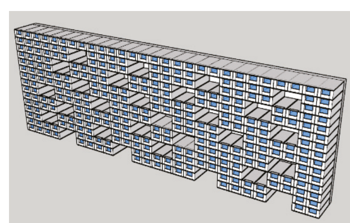


Figure 4. Costs of heating and cooling of orientation_alt1 and orientation_alt2.

4.2.4. The Alternative Design According to the Elevation Design

Since there is a difference in the number of units, the average values of units for the 2nd to the 14th floor, excluding the top and bottom floors, were compared (see Table 23).

Table 23. Layouts of base model and alternative design.

Type	Shape of the Elevation	
Base (364 units)		
Elevation_alt1 (260 units)		

- Comparison of heating load

The amount of heat gained during the heating period was the same; however, there was an increase in the heat loss as a result of the changes made to the exterior wall (71.8%), and the heating load increased by 41.5% (see Table 24).

- Comparison of cooling load

The amount of heat gained during the cooling period was the same; however, the cooling load decreased by 5.5% due to an increase in heat loss through the exterior wall (78.3%) (see Table 25).

- Comparison of annual costs of heating and cooling

With the change in the elevation design, the deviation in heating load between households increased, and the cost of heating was also 48,486–102,538 won, which increased by household. Further, the deviation in cooling load between households increased, and the average cost of cooling decreased by 5.5% (see Table 26).

Table 24. Heating load of elevation_alt1.

		Heat Gain					Heat Loss					Etc.	Annual Heating Load
		Lighting	Equipment	Persons	Solar Radiation	Total	Exterior Walls	Windows	Interior Walls	Infiltration	Total		
Base (kWh)		361	612	305	821	2099	−505	−703	−135	−1634	−2977	−14	892
Elevation _alt1	Value (kWh)	361	612	305	821	2099	−867	−694	−172	−1619	−3352	−9	1262
	Rate of change (%)	0.0	0.0	0.0	0.0	0.0	71.8	−1.3	27.3	−0.9	12.6	-	41.5

Table 25. Cooling load of elevation_alt1.

		Heat Gain					Heat Loss					Etc.	Annual Cooling Load
		Lighting	Equipment	Persons	Solar Radiation	Total	Exterior Walls	Windows	Interior Walls	Infiltration	Total		
Base (kWh)		511	867	777	1574	3728	−193	−327	−74	−660	−1254	−9	2465
Elevation _alt1	Value (kWh)	511	867	777	1574	3728	−345	−320	−86	−646	−1397	−3	2328
	Rate of change (%)	0.0	0.0	0.0	0.0	0.0	78.3	−2.0	16.5	−2.1	11.4	-	−5.5

Table 26. Deviation of costs of heating and cooling of elevation_alt1.

		Heating Costs				Cooling Costs			
		Min.	Max.	Mean	Deviation	Min.	Max.	Mean	Deviation
Base (won)		47,656	65,920	49,294	4068	133,639	140,091	139,387	1337
Elevation _alt1	Value (won)	48,486	102,538	69,807	16,395	120,747	139,480	131,651	5661
	Rate of change (%)	1.7	55.5	41.5	303.0	−9.6	−0.4	−5.5	323.4

The average costs of heating for all households increased by 41.6%; however, the costs of cooling decreased by 5.5%. As a result, the combined annual costs of heating and cooling increased by 6.8%. There was no significant difference between the south and southeast orientation (see Table 27 and Figure 5).

Table 27. Annual costs of heating and cooling of elevation_alt1.

		Heating Costs	Cooling Costs	Heating and Cooling Costs
Base (won)		49,294	139,387	188,681
Elevation _alt1	Value (won)	69,807	131,651	201,458
	Rate of change (%)	41.6	−5.5	6.8

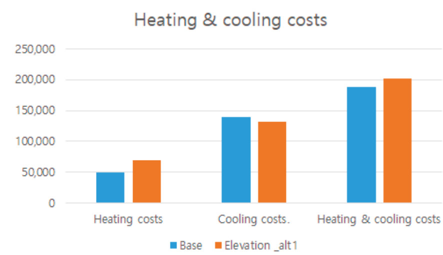


Figure 5. Costs of heating and cooling of elevation_alt1.

- Comparing the annual heating and cooling costs of the base model and all design alternatives

Figure 6 is a graph comparing the annual heating and cooling costs of the base model and design alternatives. The difference between the base model and the design alternatives was examined by separating annual heating costs and annual cooling cost. The difference between the base model and the design alternatives was examined by separating annual heating costs and annual cooling costs. However, when we examined using annual heating and cooling costs combined, the difference from the base model decreased.

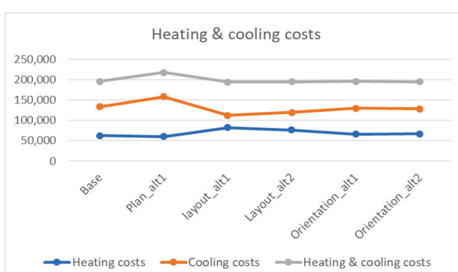


Figure 6. Costs of heating and cooling of design alternatives.

5. Conclusions

The findings indicate that the shape of a building is an important design factor in the process of optimizing energy efficiency in residential building complexes while simultaneously fulfilling the function of residential living without compromising on heating and cooling mechanisms.

This study presented feasible design alternatives and effects of design factors on heating and cooling energy loads as a whole. A housing unit which is suitable for 1–2 residents in a public rental apartment was developed and generalized in response to demographic changes for affordable options. Using the base model option, energy costs were estimated and compared with design alternatives considering both heating and cooling loads. The alternative housing unit, more square-shaped compared to the long rectangular type, resulted in a higher cost of energy. The change in the shape of the floor plan brought about a change in the window area, and the overall heating load was found to be slightly reduced; however, there was a further increase in the cooling load, resulting in an 11% increase in the total cost of energy. Furthermore, the housing complex consists of more square-shaped house units, resulting in a longer, narrower shape of the housing complex as a whole; thus, each house provides better living conditions. However, the appearance of the alternative residential building may have been similarly monotonous and more linear. Simulation results show that as the solar radiation load increases or the window area increases due to alteration of the plan, there is a simultaneous significant increase in the cooling load while the heating load decreases. It is necessary to consider the size of the window, the shielding coefficient of the window, and the shade design according to alteration of the plan ratio to improve energy savings as a whole.

The performance of the alteration of the layout suggested in this study greatly increased the heating load by between 21.1% and 31.9%, while the cooling decreased by between 10.5% and 12.9%. However, the changes in the alternative layout fail to significantly reduce the cost of energy since the climatic condition in Korea is characterized by extreme temperature differences between summer and winter seasons and higher energy cost rates for cooling. The three models incorporating orientation changes indicated a similar range in terms of the total cost of energy for a whole building. However, in the alternative layout model, the deviation values of the alternatives are much higher than those related to the base option; the households may have extremely different costs of energy depending on the location of the house unit in the residential building complex. There is a dilemma in this context when people have more design alternatives; heating and energy loads are simultaneously affected, and the cost of energy of each house also fluctuates. This result indicates that the orientation and shape of buildings—for example, layout alteration—can dramatically reduce heating costs, which is consistent with previous findings. In Korea, due to its climate, people need both heating and cooling. Thus, the energy performance or energy cost needs to be considered from both a heating and cooling perspective. Seeking design alternatives requires more than simply considering orientation and building shape. From the perspective of residents, it is important to estimate energy consumption in an integrative way that includes heating and cooling. By seeking optimal energy solutions in alternative designs, this study differentiates itself by experimenting with multiple unit formations and altering the layout of housing units relative to the simulation conducted by Lee et al. [10]. Few existing studies have evaluated the energy efficiency of residential buildings starting from a housing unit and alternate collective formations. We concluded that the change in layout proposed in this study did not apparently reduce the cost of energy, and people strongly prefer a south orientation due to climatic and cultural contexts.

To observe the change in energy performance along with the change in the elevation of the façade, we compared the energy performance between the voided and flat form of the façade/balcony. The energy performance of the voided form greatly increased the cost of heating and slightly reduced the cost of cooling. It is extremely necessary to reinforce the insulation of exposed side walls. From the findings that introducing design alternatives did not significantly reduce or increase the cost of energy, it is difficult to use design alternatives as an incentive option for saving costs; however, this also implies that the various design options do not increase cost burdens. By incorporating the building façade design, window design, shielding, and other envelope features of a building, the alternative models improve energy efficiency. Considering changing demographic characteristics and climatic conditions, housing design alternatives can provide more options for residents without causing energy burdens.

Future studies need to consider the changes in climatic conditions in terms of global warming. Increased temperature requires higher cooling loads and residential sectors may require different options. To be able to balance heating and cooling loads, more elaborate design features and other sustainable options are needed. Besides plan alterations (ratio of housing unit), orientation, layout, and elevation changes, the simulation includes other factors such as an increase in the cooling period according to changes in climate and the simultaneous effects of a combination of various design factors in an effort to achieve the optimal energy efficiency model. The energy deviation factor for public rental houses also needs to be investigated since each household can be sensitive when it comes to the energy condition and comfortable living.

Recent developments in technology have greatly improved the energy performance of materials and products, and the costs of energy for heating and cooling are also changing. Therefore, it is necessary to study the design factors in terms of energy performance in a timely manner. The results of this study are helpful in providing sustainable design solutions by balancing more diverse needs of households and the cost of energy as well as in providing more comfortable housing units. The alternative sustainable design options could be balanced by integrating housing design elements and diverse residents' housing needs as well as by considering aesthetic and economic concerns regarding public rental housing. Specifically, future designers and researchers can benefit from the assessment of energy efficiency of both heating and cooling loads for alternative south-facing building configurations.

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Appendix A

The thermal transmittance of the building used in the simulation is presented in Table A1 below.

Table A1. The thermal transmittance (U-value) of the building used in the simulation.

Part of Building		U-Value (W/m^3 K)
Exterior wall of living room	Directly facing outside air Indirectly facing outside air	0.201 or less 0.260 or less
Ceiling or roof of the living room on the top floor	Directly facing outside air Indirectly facing outside air	0.150 or less 0.220 or less
Floor in living room on the bottom floor	Directly facing outside air Indirectly facing outside air	0.180 or less 0.260 or less
Floors between levels of the property		0.810 or less
Window and door	Directly facing outside air Indirectly facing outside air	1.200 or less 1.600 or less
Front door of the household	Directly facing outside air Indirectly facing outside air	1.400 or less 1.800 or less

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Article

Design Elements in Apartments for Adapting to Climate: A Comparison between Korea and Singapore

Seo Ryeung Ju * and Jeong Eun Oh

Department of Housing and Interior Design, Kyung Hee University, Seoul 02447, Korea; meme9@snu.ac.kr
* Correspondence: jcl@khu.ac.kr; Tel.: +82-2-961-0648

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Abstract: Currently, almost 80% and 50% of Singapore's and Korea's residents, respectively, live in apartments. Despite their earlier unfamiliarity with apartments compared with traditional housing, they have accepted apartments for the convenience they offer and as a symbol of modernity. However, the climatic conditions of these countries are extremely different. Hence, this study first examined the critical regionalism that should be considered from the environmental context, such as the geography, climate, and topography, when building apartments. Reviewing the transformation process of apartments, we can determine the types of design elements and principles developed under different climatic conditions. The representative unit plans from 1960 to 2010 were collected for analysis from Singapore's Housing and Development Board and the private sector in Korea. The analysis revealed that Singapore's apartments have evolved to facilitate natural ventilation. Irregular unit forms, an atrium, and the location of the utility space are unique elements. The atrium-type apartment can be considered the most regionalized design. Conversely, in Korea, the focus is on heat gain and cross-ventilation, resulting in simple square-form units oriented toward the south and double enveloped by additional windows. The staircase-type apartment predominates. Thus, this study shows that apartments evolved differently in each country, resulting in unique regionalized forms primarily determined by climatic conditions.

Keywords: sustainability; regionalism; climate; unit plan; apartment; Singapore; Korea

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1. Introduction

Scholars widely accept that the form of a house can be considered a product of the regional culture [1,2]. A vernacular house is designed and built by the people who live in them to meet their specific needs, and therefore, accommodates their social values, religion, economy, and way of life. Since the basic role of housing is to provide shelter, these houses are connected to nature. They are built using local and natural materials, are adapted to the climate, and have a distinct identity. However, the rapid industrialization and urbanization in Asian metropolitan cities have destroyed indigenous houses, and apartments, a house form imported from Western countries has replaced them as the representative housing typology. Apartments were designed for mass supply in the most economical way, as simple concrete boxes. One criticism is that after the introduction of the apartment, houses worldwide lost their identity and became homogeneous.

Kenneth Frampton [3] emphasizes the critical regionalism that buildings should be in harmony with the environmental context, such as geography, climate, and topography. Their design does not involve directly copying vernacular architecture, but rather, combining modernism and traditional designs [4]. Since the 1980s, famous architects from Singapore and Malaysia have addressed the challenges of the tropical climate and, inspired by the environment, have successfully adopted sustainable technologies and created a sense of cohesive identity that transcends ethnicity and culture [5]. Unfortunately, their interest has been focused on monumental projects, and they have not given serious attention to apartments for the general public built by local companies. The style of apartments initially imported into Asian metropolitan cities was a simple, concrete, dormitory-style house. However, apartments are currently the most popular house type following a series of subtle adaptations during the past 60 years to meet the local people's needs. Although these apartments did not attract attention from famous architects and academic scholars, conscious efforts were made to meet the changing needs and requirements of the time. The essence of knowledge gained from vernacular houses was harmoniously incorporated during this transformation. Based on this aspect, the apartment can be defined as the modern vernacular house.

As regards apartments, Singapore and Korea are similar in that the concept of apartments was imported into both countries in the same period, and then, apartments were supplied in large numbers to solve the prevalent housing shortages. Currently, almost 80% of people in Singapore and more than 50% of those in Korea live in an apartment. However, the climatic conditions of these countries differ widely. Hence, this study is based on the idea that a comparison of the transformation process of apartments in Singapore and Korea will reveal the way they were built in response to the climate and the differences in the types of design elements and principles developed under the different climatic conditions.

To comprehend the diverse nature of the house, it cannot be approached from a one-dimensional perspective and should be approached by adopting a multidisciplinary approach, such as from the climatic and sociocultural perspectives [1,2]. Many multidisciplinary factors have influenced the development of modern apartments, such as government policies, regulations, and construction costs, which cannot be excluded from such considerations. Nevertheless, this study focuses on the relationship between the house and the climate to examine the ways in which the climatic condition influenced the evolution of a new form of housing, and as a result, the manner in which the apartment was transformed in each county in adapting to the local climate. Through examining this transformation process, we can extract design elements and principles that were invented and transformed or continued from the vernacular house that is still sustained despite the rapid technological developments and the extensive sociocultural changes. In addition, this study suggests future directions for the sustainable development of housing in Asian metropolitan cities.

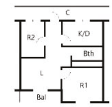
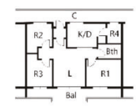
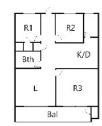
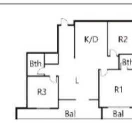
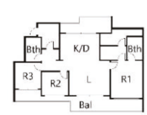
2. Research Method and Limitation

In this study, we use a qualitative approach based on case studies. We chose six cases from each country according to the period, which ranged from the 1960s to the 2010s. The sizes of units for Singapore were as follows: 2BR units, 60 m^2; 3BR units, 82–138 m^2; and 4BR units, 137 m^2. The sizes of units for Korea were as follows: 2BR units, 45 m^2; 3BR units, 84–85 m^2; and 4BR units, 75 m^2 (see Table 1).

The selection of cases is important because the cases should represent the typical unit plans for the period, and not be special cases. The cases for Singapore were selected from Teoalida's [6] website (Teoalida has constructed and operated this website since 2009. It provides collected information and publications about the HDB history, photos, statistics, and floor plans. This site is widely cited by researchers.) and the cases for Korea were selected from representative studies [7,8] on apartments (Many studies have examined the history of apartments in Korea. For this study, we selected cases from studies by Choi and Jihn [7] and the Korea Institute of Construction Technology [8].). We analyzed the cases from the perspectives of site plans, block plans, unit plans, and façade designs. We applied a qualitative approach to each topic in a comparative analysis to determine the most pertinent elements and principles, rather than a quantitative approach.

This study focuses on architectural design, not environmental science. A scientific quantitative approach is effective in demonstrating the climatic effects of design elements. However, this study aims to understand the conceptual ideas underlying the architectural design, such as space layout, space division, and design elements, rather than show how the design elements work to control climate.

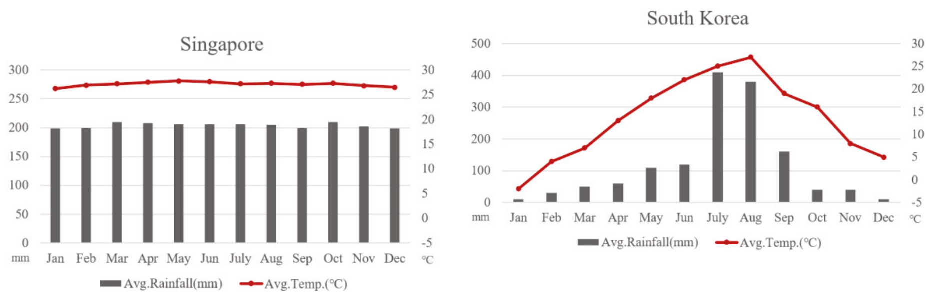
Table 1. General information on research targets.

Period	General Data	Singapore		Korea	
1960	Case Code	S-60		K-60	
	Location	All 1960s' and 1970s' estate		Mapo. A.	
	Built Year	1966		1962	
	Floor Area (m^2)	60		45	
	No. Bedroom	2		2	
1970	Case Code	S-70		K-70	
	Location	All 1970s' estates		Jamsil. A.	
	Built Year	1974		1976	
	Floor Area (m^2)	82		75	
	No. Bedroom	3		4	
1980	Case Code	S-80		K-80	
	Location	AMK, Bedok, Clememt etc.		Banpo Mido A.	
	Built Year	1980		1986	
	Floor Area (m^2)	121		84	
	No. Bedroom	3		3	
1990	Case Code	S-90		K-90	
	Location	Toa Payoh		Bundang Hanshin A.	
	Built Year	1993		1992	
	Floor Area (m^2)	137		85	
	No. Bedroom	4		3	
2000	Case Code	S-00		K-00	
	Location	Kallang Heights SERS		Tower Palace	
	Built Year	2008		2002	
	Floor Area (m^2)	121		85	
	No. Bedroom	3		3	
2010	Case Code	S-10		K-10	
	Location	Toa Payoh		Pangyo A.	
	Built Year	2012		2010	
	Floor Area (m^2)	138		85	
	No. Bedroom	3		3	

3. Understanding of Singapore and Korea

3.1. The Climate and Vernacular Housing

The climate of Singapore is hot and humid throughout the year, and the average temperature ranges from 26 to 30 °C. It has only two seasons: The wet and dry seasons. By contrast, Korea has four distinct seasons per year and an extreme temperature gap since the temperature ranges between minus 7 °C and 30 °C. Summers in Korea are very humid and hot, and winters are very dry and cold (see Figure 1).

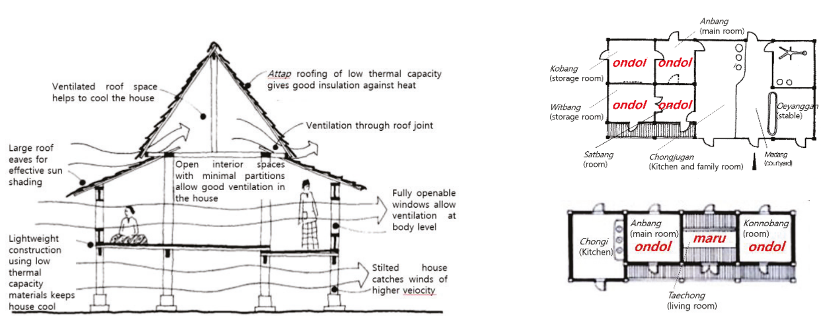


(a) **(b)**

Figure 1. Monthly temperature and rainfall: (**a**) Singapore, (**b**) Korea (source: revised form a: [9], b: [10]).

The vernacular houses of Singapore originated from the Malay house, a timber house raised on piles. Many clever ideas were implemented to ensure a pleasant, safe living environment. The most important one is the attempt to maximize ventilation throughout the house. The lifted floor on piles allows cool air to pass beneath the floor. Windows are designed as open to facilitate cross-ventilation. The double-layered high gable roofs with an opening on top have distinct advantages in extracting heated air even when it is raining [11] (see Figure 2a).

In Korea, the houses must be built to manage the extreme temperature gap between summer and winter. A duality is found in the architectural designs of houses in Korea [12] (p. 11), that is, two different design elements coexist in the Korean vernacular house: "Ondol", which is a heated floor for winters, and "maru," which is a wooden floor lifted from the ground for summers. Although the national land area is small, different types of houses have been developed in each region. In the houses located in the north (the cold region), the rooms have double layers without an open space (maru) and a simple square form to retain heat. In the houses located in the south (the warm region), the rooms are aligned in a row and the maru is located in the middle. This open design is more advantageous for cross-ventilation (see Figure 2b).



(a) **(b)**

Figure 2. Sustainable design of vernacular housing: (**a**) Malay vernacular house, source: [11], (**b**) Korean vernacular house: (**Top**) north region (**bottom**) south region, source: [12]. Ondol: Heated floor, maru: Wooden floor.

3.2. The Short History of Apartments

Singapore is the first country in Southeast Asia to popularize the apartment, and 80% of its population stays in the Housing Development Board (HDB) apartments supplied by the public sector. Singapore's housing supply rate rose from 9% in 1960 to 90% in 1990, which is a short period, and provided the foundation for the stable growth of the country. HDB has provided standard unit plans for mass supply. The standard plans were upgraded periodically, but they were too monotonous to meet residents' diverse lifestyles when compared with private condominiums. Since the 1990s, HDB has turned its attention to providing quality housing. It offers a wider choice of housing, ranging from executive condominiums and housing cooperatives to new flat designs. A formal upgrading program has resulted in a complete change in perceptions regarding HDB housing [13].

In Korea, the apartment was introduced after the Korean War to solve the problem of a mass shortage of housing supply. The supply was led by the private sector, which is different from the case of Singapore. When apartments were first introduced, people avoided them owing to their unattractive, uniform shapes and the unfamiliar lifestyle they offered. However, through a transformation process to adapt the apartment to the Korean lifestyle, it was recognized as a representative middle-class house.

In both countries, apartments were supplied to solve the urgent housing shortage problem after the countries made a new start in the 1960s. Despite its lack of similarity with the traditional housing culture in the early period of its adoption, the apartment has been accepted by people as a home that offers convenience and is a social symbol of modernity.

4. Results: Site Plan, Block Plan, and Unit Plan

4.1. Site Plan

Since ancient times, Koreans have believed that feng shui is based on principles of nature governing the spiritual forces that operate the land as well as the underground area. Hence, the location and direction of a house were decided based on feng shui. They believe that feng shui is not only a philosophy but is also scientific knowledge. It offered them the wisdom to adjust to the local climate and geography to receive and avoid sunlight and take advantage of seasonal winds of the region. A strong belief based on feng shui was that the house should be oriented toward the south.

This strong desire for a south orientation was continued in selecting an apartment. When apartments began to be built in Korea, it was difficult to sell them if this requirement could not be met. Therefore, apartment blocks were designed as long buildings, stretching from the east to the west, to ensure that as many units as possible faced southward. Consequently, the blocks were placed in parallel, similar to military barracks. In this layout, the living rooms and bedrooms almost exclusively faced the south. In the tower-type apartments built later, the orientation of units could be varied owing to the layout. Despite this layout, the tendency to orient units toward the south prevails.

In Singapore, the orientation of blocks and the position of the courtyard and balconies were carefully considered to respond to climatic conditions [14], but apartments were not oriented toward one direction, unlike in Korea (Figure 3). As regards the site plan, most early Singapore apartments were arranged with the inner courtyard surrounded by long blocks of buildings. In this case, regardless of the orientation of the sun, the kitchen or bathroom faced the inner courtyard, whereas the public corridors faced the outside of the courtyard.

(a) (b)

Figure 3. Site plan: (**a**) Singapore: The service areas were located toward the courtyard, Blk336 Bukit Batok street 33, built in 1985, source: [15]. (**b**) Korea: The blocks were placed in parallel. Daechi Eunma Apartment, built in 1979, source: [16].

4.2. Block Designs

In both countries, the blocks of early apartments had a long corridor-type design, which was an economical way to secure high density. In Singapore, this type was transformed into the atrium type, which has been generalized since the 2000s for increasing the density. The atrium-type block means that two linear corridor-type buildings are attached back to back, and building cores, such as staircases, elevators, and the atrium, are located in between the two buildings. In this case, service spaces, such as the kitchen and the bathroom of each unit, are located around the inner atrium and are not exposed to the outside of the building. The mixture-type block plan, which appeared later, is a more advanced version of the atrium type for a building that has less density. The building is fragmented into a couple of units. The atrium is bigger and is open to the outside and thus receives more daylight and air than in the other building types.

In Korea, the long corridor type was first transformed into the staircase type and later to the tower type. The staircase-type block plan is unique to Korea. As explained in Section 4.1, Koreans desire south-oriented houses, and therefore, a long corridor-type design should be a solution, but this type is weak as regards the aspect of ensuring the privacy of units. In the staircase type, only two units share their cores and the two sides (front and back) of a unit face the outside directly. Therefore, the privacy of units is not an issue and they have increased cross-ventilation as well as a better view from both sides.

During this transformation process, the forms of unit plans within blocks were changed from narrow and deep to wider and shallow. This phenomenon can be explained as an attempt to improve the quality of the residential environment of units, such as the ventilation, the view, and access to sunlight.

In the transformation process of the block plans in Singapore, the service spaces (the kitchen and bathrooms) were consistently arranged to receive fresh air from outside and to be hidden from the façade of the buildings. However, in Korea, the rules related to the south-facing unit were maintained regardless of the block type (see Table 2 and Figure 4)

Table 2. Block plan analysis.

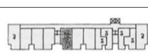
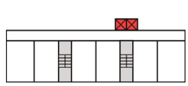
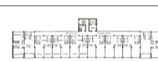
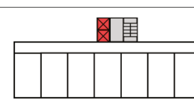
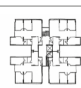
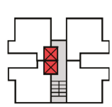
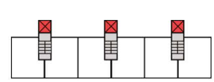
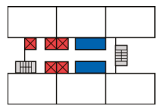
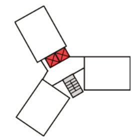
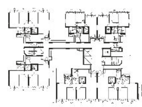
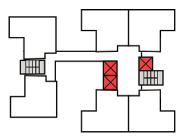
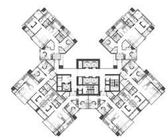
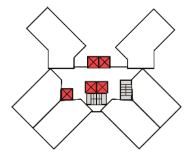
Period	Singapore		Korea	
1960–1970	 Slab Block		 Corridor Type	
1980–1990	 Tower Block		 Staircase Type	

Table 2. *Cont.*

Period	Singapore		Korea	
2000	 Atrium Block		 Tower Type	
2010	 Mixture Block		 Complex Type	

EV; Atrium.

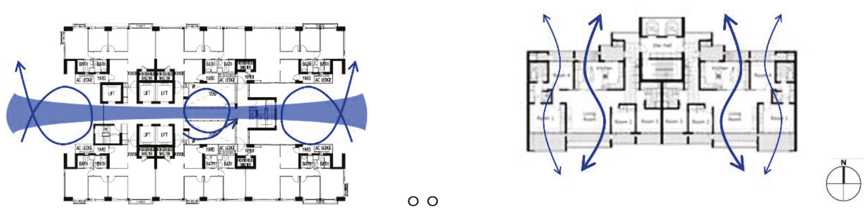


Figure 4. Representative block plans: (**a**) Singapore: The service spaces (kitchen, bathroom, and yard) face the inner core space and the atrium in the atrium-type block plan. (**b**) Korea: In the staircase-type block plan, more rooms face south and cross-ventilation becomes effective.

4.3. Unit Plans

4.3.1. Living Room

In Singapore's early apartments, the living rooms were located near the entrance (back) and the service areas, such as the kitchen and the toilet, were located far away from the entrance and faced the outside (front). In this case, the temperature of the living room can be effectively reduced by blocking the sunlight, but the privacy and view of the living room are sacrificed. This layout helps to release odors and moisture in narrow, long units. This layout is unique to Singapore, and our analysis reveals that it maximizes the natural ventilation of service spaces in the hot, humid climate.

Recently, the forms of units in Singapore have been widened horizontally, and the positions of the kitchen and living room have been reversed. That is, the living room is placed in the front and the kitchen at the back near the entrance, following contemporary high-end styles that prioritize providing the best possible view from the living room. This change is driven by technological developments, such as super-high-rise building construction and mechanical ventilation (see Table 3 and Figure 5a).

In Korea, ensuring that buildings had the south-facing, wide, and shallow shape and the "two-side open unit" design that allows cross-ventilation was the rule that had to be observed throughout the study period, regardless of the block type. This rule produces a unit that has a long surface, which increases the sunlight entering the unit, secures a good view, and ensures cross-ventilation such that air passes from the front of the unit to the back (see Table 3 and Figure 5b).

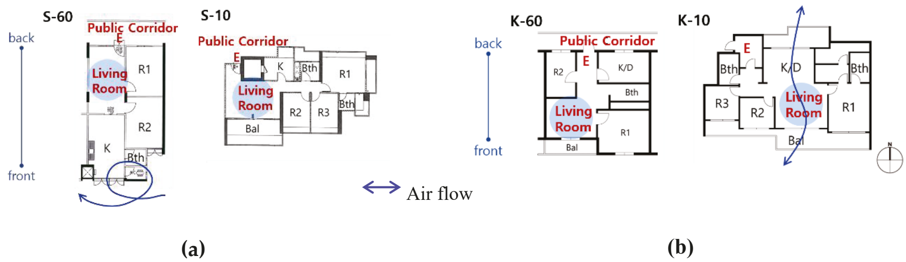


Figure 5. The location of living rooms: (**a**) Singapore: Reversing the location of the living room during the period. (**b**) Korea: The living room is always oriented toward the south.

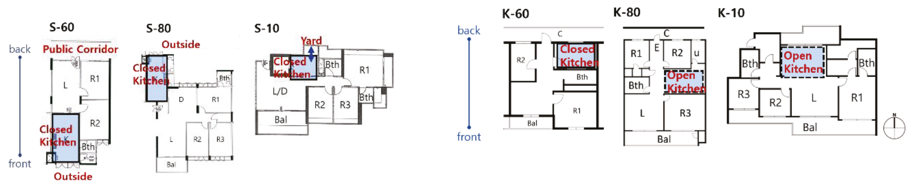
4.3.2. Kitchens

In early apartment units in Singapore, kitchens were located at the front, facing the outside, and separated by a wall from the living room. This closed kitchen was dominant throughout the period. The closed kitchen is beneficial to prevent the spread of heat and moisture from the kitchen. This layout is also linked to the traditional culture (see Table 3 and Figure 6a).

In traditional Malay houses, a hierarchical division of space occurs between public and private spaces. People can enter the house from the public space (anjung, serambi) to the private space (rumah ibu, dapur) (The anjung, a covered porch where guests are greeted, social interaction takes place, and family members relax, constitutes public space. The serambi, where male guests are entertained and social and religious functions take place, is also regarded as public space. Conversely, the most private space in the house is the rumah ibu, where family members sleep, pray, and do household tasks and other daily activities. Located at the back of the house, the dapur, or kitchen, is the private space for females. The selang, which links the rumah ibu to the dapur, is considered semi-private space.). Visitors are not allowed to enter the private space unless they are family members or female guests. The kitchen (dapur) was regarded as a dirty space owing to anthropomorphism (Anthropomorphism is one of the key concepts commonly embodied in the traditional Malay houses. It is believed that the form and order of traditional houses are based on those of the human body. The houses can be divided vertically into three sections that resemble the anatomy of the human body: Roof (head), habitable space (torso), and piles (legs). The association between the house and human body also exists horizontally, with the serambi in the front of the house representing the face, and the dapur—the kitchen located to the back of the house—representing the anus. The practice of throwing away daily refuse, such as food scraps, through the back of the kitchen has been likened to the act of defecation [17].). This tradition explains why the kitchen and bathroom are located as far as possible from the entrance.

Further, in Singapore, until recently, hiring maids was a common practice. The social segregation between the owner and the maid meant that the latter's space was separated from the main space in independent houses, and this idea was also implied in a modern apartment unit. Moreover, a recent trend is to divide dry and wet kitchens in large-sized condominiums. With this trend, closed kitchens are gradually being changed to an open kitchen, and the kitchen is recognized as a living space instead of as a utility space.

By contrast, in Korea, the location of the kitchen is not fixed. It can be located at the back or in the middle of a unit, but an open kitchen is dominant. Except the very early period, the kitchen is regarded as a living space for the family and connects the dining and living rooms. The issues related to the ventilation of the kitchen can be solved thanks to the two-side open layout and mechanical ventilation (see Table 3 and Figure 6b).



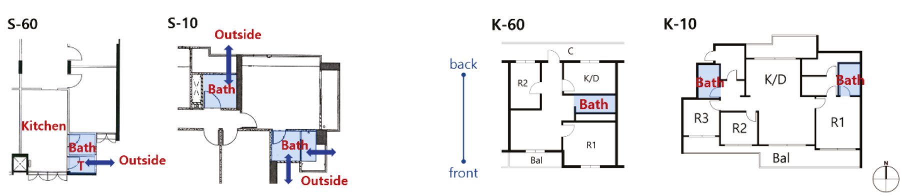
(a) **(b)**

Figure 6. The location of the kitchen: (**a**) Singapore: The kitchen always had outside air and was designed as closed from other spaces. (**b**) Korea: The location of the kitchen was not fixed, and it was designed as open to other spaces.

4.3.3. Bathroom

In the early Singapore apartment, the bathroom can be approached through the kitchen, which is a very unique layout, hardly found in other countries. The kitchen and bathroom are designed as one service zone and divided into a separate space from the other spaces of the unit. The design can be understood to be based on the same reasons, namely, to prevent the spread of moisture occurring in the kitchen, to comply with the anthropomorphism culture and to maintain the order found in traditional houses (see Table 3 and Figure 7a).

In Korea, the bathrooms are usually in the middle of a unit and do not have windows. During the winter, it is too cold to wash in a bathroom with a window even when heating was installed there. Therefore, a bathroom without windows and placed in the middle of the unit was favored for thermal insulation. In these circumstances, the ventilation of the bathroom relies on advanced mechanical systems (see Table 3 and Figure 7b).



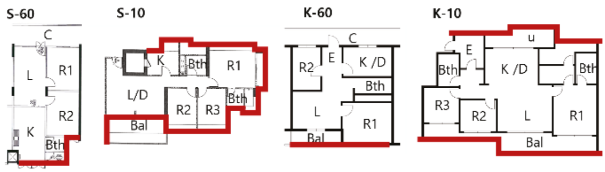
(a) **(b)**

Figure 7. The location of the bathroom: (**a**) Singapore: In the early period, the bathroom and toilet can be approached through the kitchen, (**b**) Korea: The bathrooms are always in the middle of the unit for thermal insulation and lack windows.

5. Results: Façade Design

5.1. The Surface of Units

The surface of the Singapore apartment's unit has many irregularities, and hence, the total length of the surface is large. These irregularities became more complex over time. This uneven form is advantageous for heat dissipation and air circulation (see Table 4 and Figure 8a). Conversely, Korea's apartments have a comparatively simple square form, which facilitates heat preservation. The short length of the surface helps to increase insulation performance and reduce construction costs and defects (see Table 4 and Figure 8b).



(a) (b)

Figure 8. Surfaces of units: (**a**) Singapore, (**b**) Korea.

5.2. Window Design

Most of the windows in Singapore apartments are single-layer, large casement windows, whereas in Korea, the apartments mostly have double-layer windows. Since the number of floors has increased to more than 30 recently, the curtain wall system of windows or system window is used in both countries. Even in the curtain wall system, residents in Korea install additional windows for thermal insulation (see Table 4).

Securing natural ventilation through windows has been common in both countries. However, because of serious air pollution and the emergence of super-high-rise apartments, windows are rarely opened. Moreover, as the popularity of the curtain wall system increased, the operation of air conditioners became more common due to the increase in cooling loads (see Table 4 and Figure 9).

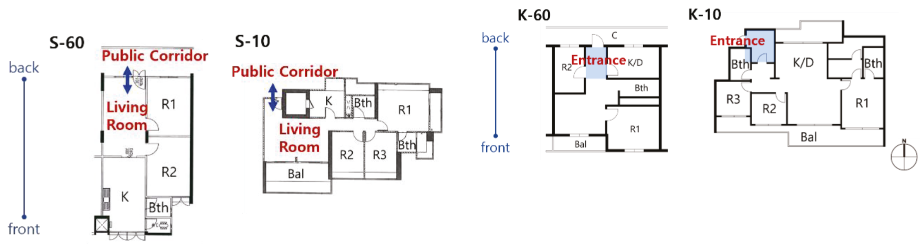
(a) (b)

Figure 9. Window types: (**a**) Singapore (single-layer), (**b**) Korea (double-layer).

5.3. Main Entrance

Most Asians take off their shoes when they enter a house. A transitional space is provided between the public corridor and the living space to take off shoes in buildings in Korea, unlike in Singapore. Singapore houses do not have a designated space called an entrance. Shoes are often placed in the public corridor. However, in some HDB apartments and condominiums, a transitional space emerged where residents remove their shoes and store them. An iron grille door is installed to protect the house from trespassers when the main entrance door is open for natural ventilation (see Table 4 and Figure 10a).

By contrast, apartments in Korea have a designated entrance space where people remove their shoes and store them, and the floor level of an entrance is lower than the level of a living room for clear distinction of in and out. In some cases, a sliding door is installed between the entrance and living room for retaining the heating energy in winter and for sound insulation (see Table 4 and Figure 10b).



(a) **(b)**

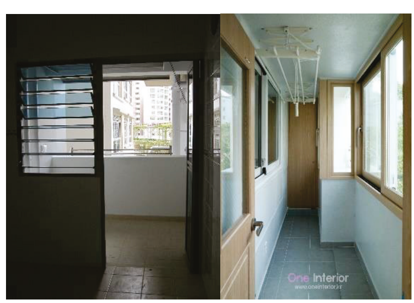
Figure 10. The relation between the public corridor and entrance: (**a**) Singapore: Direct access to the living room without entrance space from outside, (**b**) Korea: Separated entrance space.

5.4. Balcony, Yard, and Public Corridor

Singapore's apartments have open balconies in front of living rooms, which are deep enough for outdoor activity. They create shade and act as an outdoor space for the residents. Korea's balconies are shallow in terms of depth and long, and they often cover the entire surface of a unit. In the early period, the balconies were substitutes for the outdoor space of landed houses, that was used for purposes such as drying clothes and storing traditional preserved food. The balconies provide shade in summer and an air layer in winter. Nowadays, balconies are mostly renovated into an indoor space to expand the house area, but still retain heat effectively owing to the improved performance of current window systems.

A yard means a service space that is a unique space found in Asian apartments for washing and drying clothes and for extra storage and is connected with the kitchen. In Singapore, it is obligatory to expose a yard to the outdoors. In Korea, a yard is usually called a back balcony or utility space and is covered by additional windows. It is used as an additional indoor utility space for cooking food that emits strong smells and for installing a washer and dryer and an extra refrigerator for kimchi.

In a public corridor in Singapore, no windows are installed, and they are exposed to the open air. By contrast, in Korea, the public corridor was covered by a window and was designed as an indoor space (see Figures 11–13 for illustrations of these design elements and Table 4 for an analysis of the façade design).

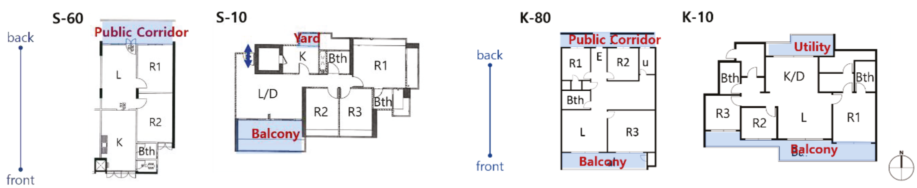


(a) **(b)**

Figure 11. Utility space: (**a**) Kitchen should have a yard facing the outside air in Singapore. (**b**) The service balcony is sealed with a window in Korea.

(a) **(b)**

Figure 12. The public corridor of the block: (**a**) The public corridor is open to the outside in Singapore. (**b**) In Korea, it is also common to seal public corridors using additional windows.



(a) **(b)**

Figure 13. Balconies, public corridor, and yard: (**a**) Singapore: Since the 1990s, balconies in front of the living room and a yard connected with the kitchen have appeared. Both are open and without windows. (**b**) Korea: Balconies are at the front and rear, and windows are installed to expand the interior space or to form air layers.

6. Comparison: Design Elements Adapted to Climate

Through the analysis, the design elements and principles that have been developed to adapt to the climate in Korea and in Singapore are summarized as follows.

6.1. Singapore

In Singapore's apartments, the orientation of buildings and rooms is not important. In the early period, the kitchen and the bathroom were located at the front in direct contact with the external environment for natural ventilation. The living room faced a public corridor, thus sacrificing privacy and daylight. This layout is effective in lowering the room temperature and blocking humidity, and it reflects the traditional spatial order of entrance–public space–private space.

The atrium-type block plan, which appeared in the 2000s, can be considered a well-regionalized plan to adapt to a tropical climate and a traditional culture, uniquely found in Singapore and Malaysia. Around the atrium are located the kitchen, bathroom, and yard of each unit. As the height of the building increases, the stack effect increases because of the substantial temperature differences, which enhances the ventilation of the utility space. In this block plan, the location of the kitchen and the living room in the previous HDB unit were reversed, and thus, the living room gained the view and the privacy that the kitchen used to have.

Thus, this change transformed the unit plans. The location of the living room moved from the back to the front, the location of the kitchen and the bathroom moved from the front to the back. The kitchen was changed from a closed space to open to the living room. In addition, the simple rectangular shape of a unit became more irregular with a long surface, allowing almost every room to be in contact with outside air. The primary issue in designing the apartment unit during this transformation in Singapore was to maximize the natural ventilation to match that available in vernacular houses.

6.2. Korea

Orientating as many units and rooms as possible to the south is a critical mission for successful marketing because people strongly prefer a south-oriented house. This belief originated from feng shui, but it can be explained as a way to receive more heat during winter and block the sunlight during summer. In early apartments, the buildings were located in parallel to allow the maximum number of units to face the south. Koreans love cross-ventilation, a strong wind penetrating the two opposite sides of a house during the summer. In early corridor-type buildings, this design caused privacy and security problems. To solve this issue, the building was changed from a corridor type to a staircase type.

With this change, the form of units changed from narrow and deep to wide and shallow. The wide and shallow unit form was advantageous in that it allowed locating more rooms to have south orientation and cross-ventilation. Moreover, it was possible to surround the surface of the unit with long balconies, where balconies served as a double envelope and a greenhouse. After giving priority to locating rooms in the south, the other spaces, such as the kitchen and the bathroom, had to be located at the back or in the center of a unit. In comparison with Singapore, the location of the kitchen is flexible. However, a preference developed for locating the bathroom in the center of the unit. It did not have windows so that the room temperature could be maintained. Thus, to Koreans, the thermal condition of the bathroom is more important than ventilation.

Summarizing the above discussion, the staircase-type block plan is a well-regionalized plan to adapt to a local climate and the traditional culture, uniquely found in Korea. Although it was criticized because of its uniform façade and inefficiency in elevator sharing, it was customized to satisfy the housing needs of Koreans. It can be concluded that the invention of new design elements in apartments in Korea focused on ensuring thermal preservation for winter and cross-ventilation for summer.

Table 3. Analysis of primary spaces in units.

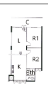
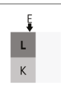
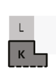
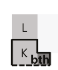
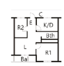
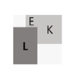
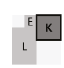
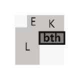
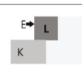
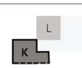
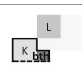
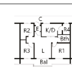
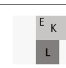
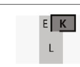
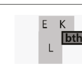
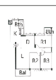
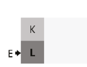
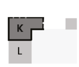
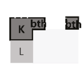
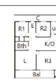
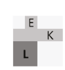
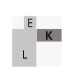
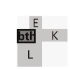
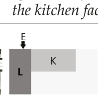
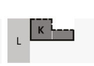
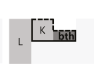
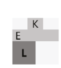
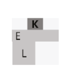
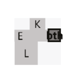
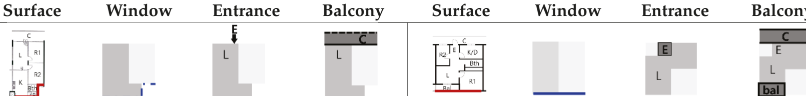
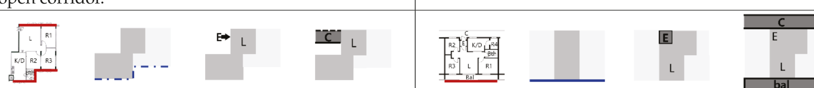
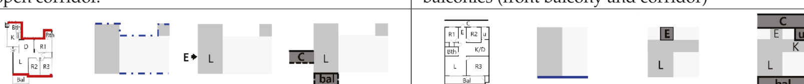
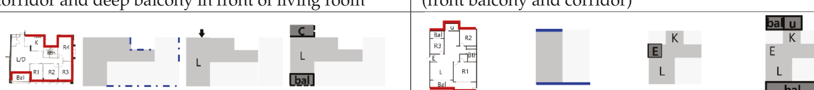
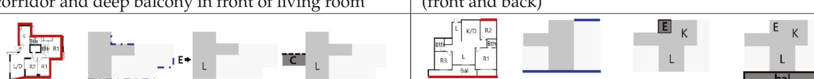
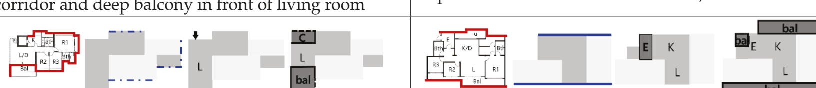
Period	Plan	Living room	Kitchen	Bathroom	Plan	Living room	Kitchen	Bathroom
1960								
	Living room facing corridor, closed kitchen, bathroom in the kitchen facing front outside (front).				*South-facing living room, closed kitchen, bathroom in the middle of a unit without window.*			
1970								
	Living room facing corridor, closed kitchen and bathroom in the kitchen facing front outside (front).				*South-facing living room, half-open kitchen, bathroom in the middle of the unit without window*			
1980								
	Living room facing outside (front), closed kitchen and bathroom in the kitchen facing outside (back).				*South-facing living room, open kitchen, bathroom in the middle of the unit without window*			
1990								
	Living room facing outside (front), closed kitchen and bathroom in the kitchen facing outside (back).				*South-facing living room, open kitchen, bathroom in the middle of the unit without window*			

Table 3. *Cont.*

Period	Plan	Living room	Kitchen	Bathroom	Plan	Living room	Kitchen	Bathroom
2000								
	Living room facing outside (front), closed kitchen and bathroom in the kitchen facing outside (back).				*South-facing living room, open kitchen, bathroom in the middle of the unit without window*			
2010								
	Living room facing outside (front), closed kitchen facing outside (back), separated bathroom.				*South-facing living room, open kitchen, bathroom in the middle of the unit without window*			

Wall; Window.

Table 4. Analysis of façade design.

Period	Surface	Window	Entrance	Balcony	Surface	Window	Entrance	Balcony
1960								
	Uneven wall of service space, single casement window with large opening, direct access from corridor and open corridor.				Flat and short walls, sliding double-layer windows, Separated and lowered floor entrance, open corridor			
1970								
	Uneven wall of service space, single casement window with large opening, direct access from corridor and open corridor.				Flat and short walls, sliding double-layer windows, Separated and lowered floor entrance, Closed balconies (front balcony and corridor)			
1980								
	Uneven wall of service space, single casement window with large opening, direct access from corridor, open corridor and deep balcony in front of living room				Flat and short wall, sliding double-layer windows, separated and lowered floor entrance, closed balconies (front balcony and corridor)			
1990								
	Uneven wall of service space, single casement window with large opening, direct access from corridor, open corridor and deep balcony in front of living room				Flat and short facade, sliding double-layer windows, separated and lowered floor entrance, closed balconies (front and back)			
2000								
	Uneven wall of service space, single casement window with large opening, direct access from corridor, open corridor and deep balcony in front of living room				Flat and long walls, sliding double-layer windows, separated and lowered floor entrance, closed balconies			
2010								
	Uneven wall of service space, single casement window with large opening, direct access from corridor, open corridor and deep balcony in front of living room				Uneven and long walls, system widows, separated and lowered floor entrance with extra door, closed balconies			

Single-layer window; Closed balcony; Entrance; Double-layer window; Open balcony.

7. Conclusions

Singapore and Korea, with very different climates, imported the concept of the apartment from the West. The apartment was a new prototype of housing, in a similar era, but evolved in different ways in each country, resulting in unique regionalized forms.

This study hypothesized that the prime determinant of these unique forms is the climate. Through the analysis of this study, we showed that this hypothesis is true and explained the major design elements that have been developed to adapt to local climate in the process of evolution of apartment design in the study period.

As regards the aspect of the site plan, the south orientation is critical to capture solar heat in Korea, while orientation is not important in Singapore. In terms of shape, units have become wider in both countries with the progression of the study period. However, those in Singapore have become more irregular to facilitate the dissipation of heat from the inside, while those in Korea have kept simple square forms as it is easier to seal a building with additional windows (double-layer windows) to keep the heat inside.

The block plan of the two countries has evolved in opposite directions. In Singapore, the block plan has changed to facilitate more natural ventilation in public corridors. The airwell (atrium) concept of the early urban shophouse has been modified and adopted as a climatic control device in tropical cities. This atrium block plan can be widely applied, and many variations are found in high-density residential projects in other metropolitan areas with similar climatic conditions. The staircase block plan is uniquely found in Korea, and even though the density of units cannot be maximized with this type, it is preferred because it provides natural cooling in summer and captures solar energy in winter. Despite these advantages, the staircase block plan is not readily applied to other countries because the design is complicatedly intertwined with local housing policy, regulations, construction cost, and diverse sociocultural factors.

The unit plan in the two countries has also changed during the study period. Up to the 1970s, the kitchen was located at the front of the unit in Singapore, which is generally opposite to other countries, as ventilation of the kitchen was more important than that of the living room at that time. Since the 1980s, the location of the kitchen has been reversed, although ventilation is still carefully considered, with the kitchen essentially communicating with an open yard. In Korea, there have been trials to determine the optimal location for the bathroom in the unit. For ventilation and good natural light, it is advantageous to locate the bathroom at the front or back of the unit, but this makes it difficult to maintain a comfortable temperature during winter even if a heating system is installed in the bathroom. Therefore, the bathroom is generally located in the middle of the unit, without windows.

Following the active construction of super-high-rise apartments in both countries, universal techniques, such as air conditioning and the curtain wall construction system, have been widely applied. As a result, the internal space of buildings has become sealed and separated from the external space, which is in contrast to the sustainable design strategy that we discussed. With this thermal modernity [18], trials for innovation of new devices for adapting to the local climate are no longer considered necessary, and the apartments of Korea and Singapore tend to be similar with the acceptance and adoption of these universal techniques and an international lifestyle.

Despite this global trend, the housing culture of each country does not change easily, tending to retain its identity and continue as before. As a basic human need, people feel comfortable in the natural thermal environment. To meet these needs, new thermodynamic projects have emerged to break the "sealed" indoor space by forming an innovative climatic relationship between the internal and the external spaces [19]. For a sustainable future, it is important to provide a home with a naturally comfortable environment to the maximum extent possible, instead of blindly relying on technology, applying the lessons from this study.

It is not easy to comprehend the diverse nature of the apartment, but this study provides a new perspective that the design elements and principles that have evolved during the last 60 years in each country are the products that people have searched for to improve quality of life by ecological methods, and not the result of adopting popular changes in architectural design styles.

It is anticipated that the findings of this study may serve as guidelines for forthcoming global residential projects. Although the designs revealed in this study may not be directly applicable to these projects, they may be suitable to be modified for the regional context and serve as a springboard for people to realize their own identity of home. For this purpose, the research on and the applications of environmental knowledge from the vernacular architecture should be continued in diverse ways, and a careful analysis of local people's needs should be included in designing homes.

Author Contributions: J.E.O. composed this study, designed the evaluation framework, completed analysis and visualization. S.R.J. provided her supervision of all the research process and substantially contributed to the methodological design and critical analysis. All authors have read and agreed to the published version of the manuscript.

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A Framework of Smart-Home Service for Elderly's Biophilic Experience

Eun Ji Lee [1] and Sung Jun Park [2,*]

[1] Department of Architecture, Keimyung University, Daegu 42601, Korea; yej@stu.kmu.ac.kr
[2] Department of Architectural Engineering, Keimyung University, Daegu 42601, Korea
* Correspondence: sjpark@kmu.ac.kr; Tel.: +82-53-580-5765

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Abstract: Smart-home technology and related services can reinforce a person's experiential nature, promoting sustainable living among the elderly. It is crucial in the housing industry that support "Aging in Place", contributing to the contact, control, and simulation of nature at home as well as the creation of a high-quality living space instead of mechanical achievement. Further, biophilic experience, the strengthening of inherent human propensity to nature for optimal health and well-being, supports the elderly's physical, mental, and sociological health. However, despite the continuing emphasis on the benefits of residential nature experiences for the elderly, the application of smart-home technology and services is insufficient. This study presents a theoretical basis for combining biophilia and smart-home technology, providing a framework for smart-home services to ensure elderly residents can have biophilic experiences. In this study, smart-home components and related studies that can support the biophilic experience and the corresponding technology are analyzed. The results suggest the type and content of smart-home service for ensuring a biophilic experience, while also indicating the configuration of supportive input and output devices according to the service framework. Moreover, we recommend the interaction characteristics of smart-home devices from the perspective of residents, space, efficient service provision, and physical application. This paper broadens our understanding of the sustainable, residential-environment nature experience and informs the expansion of the aged-friendly smart-home industry, contributing to smart-home services trends and development.

Keywords: elderly; biophilia; biophilic experience; smart home; smart-home service; service framework

1. Introduction

The most important factor in the residential space for the elderly is their experience, and the main objective is to induce and support experiences related to health and well-being. The priority of the elderly experience in a residence should take into account the fundamental needs of the elderly and the resulting benefits. In particular, it is very important for the elderly to maintain constant contact with nature in their physical environment and to stay healthy. "Biophilia" is a concept that explains the relationship between humans and nature and is defined as "the inherent need among humans to interact and mingle with nature in order to achieve and maintain their optimal health and well-being" [1]. Biophilia has a positive impact on the elderly in terms of productivity and emotional well-being, stress reduction, learning, and recovery [2,3]. Moreover, related studies have mentioned that biophilia provides practical help to the elderly, which can be measured or proven [4–7]. Accordingly, biophilic design is being applied to medical and nursing facilities for the elderly [8], and the active attitude of the elderly toward successful aging and the pursuit of "Aging in Place" (AIP) emphasizes the need to connect with nature in residential spaces.

AIP has been a popular topic in social welfare academia in recent years, and it is deemed meaningful because it forms a community care service network in residential spaces that considers economic and efficiency aspects and allows aging with familiar people in familiar areas [9]. It should be noted that services supporting AIP are developing with technological advancements. As the "baby boomers", people who were born in the period of markedly increased population, are integrated into the aging population, the conventional concept of the "elderly lifestyle" is changing, showing a different pattern from that of the previous generation [10]. Currently, smart technology occupies a large part of the elderly's daily life, and the concept of "smart aging", which considers the acceptance and understanding of technology by the elderly, has a great influence on the intelligent housing industry [11]. Smart homes for the elderly focus on providing efficient healthcare and convenience, such as real-time monitoring systems and remote medical treatment, fall detection and response, security, and safety management. Even though biophilia has long explained the importance of nature on health and welfare [1,2,12–15], few studies have investigated smart-home services that support and connect the elderly to nature. Contemporary smart healthcare services are useful for treating diseases and responding to emergencies; however, planning techniques that expose the patients and the elderly to a healthy natural environment could be more important, as they can provide the opportunity for the elderly to maintain a good health. This is a problem that requires adequate and thorough research. The natural environment closely affects human health, and its deprivation causes disorders such as fatigue, depression, high blood pressure, diabetes, and cancer [16–18]. Therefore, from a preventive perspective, it is necessary to find a methodology that can induce biophilic experiences to help the elderly living in urban environments, where the natural environment is scarce, to maintain a healthy life.

The purpose of this study is to suggest a theoretical basis for combining biophilia and smart-home technologies and to provide a framework by designing smart-home service content for the elderly in residential spaces. The concept of biophilia is not contrary to industrial and urban development, and it can act as a catalyst for key elements of building-related technologies. Smart lighting, heating, ventilation, and air conditioning (HVAC) control systems in the field of architectural planning are elements that can maximize contact with nature, and the use of Internet of Things (IoT), Virtual Reality (VR), and Augmented Reality (AR) technology enables an increase in the effectiveness of natural production in a limited physical environment. The health benefits associated with experiencing nature arise from the opportunity to perceive it rather than from direct contact [19], and this includes natural analogs such as shapes, colors, and sounds that can remind us of nature through images [1,8,19]. In addition, recent studies have demonstrated the healing effect of the natural environment based on virtual reality [20–22]. In other words, the use of IoT can help resolve the problems of physical and spatial limitations and the physical environment in residential spaces, enabling a satisfying experience with nature. Figure 1 shows the scheme used in this research.

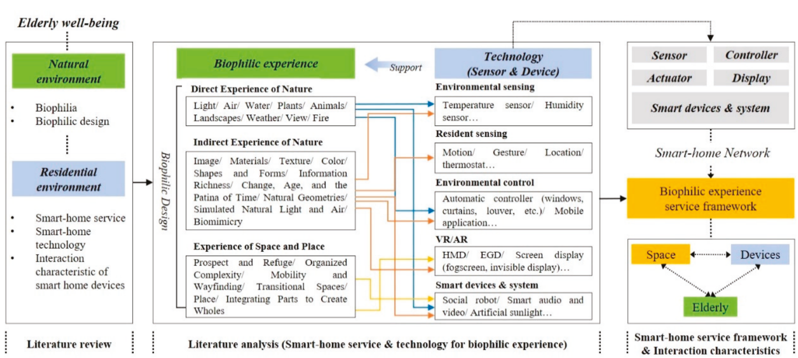

Figure 1. Research scheme.

First, to achieve the aim of this study, current research is reviewed in relation to the natural environment and in terms of the effects of biophilia on the health of the elderly, i.e., the concept of biophilic experience. In addition, the existing smart-home service fields and components are analyzed, focusing on studies related to the residential environment and smart-home service for the elderly. Second, through literature analysis, the link between the key elements of the biophilic experience [23] and the smart-home services and technologies related to the health of the elderly are systematically analyzed according to three categories. The literature analysis of this study was performed through major academic databases, including Scopus, IEEE Xplore, SpringerLink, ScienceDirect, and PubMed, and is described in detail in Section 3. Third, we propose a service framework by constructing the contents of the biophilic experience-based service of the elderly with regard to smart-home technologies and devices. Finally, the input and output devices that can support biophilic experience services according to the service framework are listed. Additionally, the interaction characteristics of smart-home devices are proposed from the perspective of residents and in terms of the available space, while also considering efficient service provision and physical application in the house.

Previous studies have focused on combining architectural elements concerning physical spatial planning, based on the concept of biophilia. This study is novel because it seeks to link smart-home services and biophilic experience in the realization of AIP and the change in perception of the elderly, targeting residential environments that lack exposure to nature. This study highlights the need for smart-home technology to support experiences with nature for a sustainable living environment for the elderly and discusses its potential. Human-centered smart-home services based on biophilic experience play a fundamental role in inducing active and independent living of the elderly. The results of this study inform the expansion of the field of the aged-friendly smart-home industry and contribute to the theoretical basis for encouraging the biophilic experience and the development of smart-home services and technology.

2. Theoretical Insights and Background

2.1. Aging and the Natural Environment

According to the World Health Organization (WHO), health is defined as having complete physical, mental, and social well-being as well as being free from disease and functional impairment [24]. Advances in science and medical technology have enabled the treatment of various diseases and have extended life expectancy; however, this does not guarantee a "healthier life." The essence of the aging problem in a global aging population is not that older people live longer, but that they do not live a healthy lifestyle. In old age, they experience not only certain diseases, but also uncomfortable conditions such as chronic fatigue, pain, depression, and sleep disorders [25]. Financial status, income level, and social relations tend to decline after retirement, while emotional complications increase [26]. In addition, a decrease in sensory functions such as visual acuity, hearing, and touch can also affect agility, balance, muscle strength, and endurance, as these are closely related to cognitive and mental health as well as physical health [27,28]. Specifically, the decline in cognitive and mental health of the elderly affects memory, language function, and information processing speed, and the elderly may experience avoidance, anxiety, and lethargy, accompanied by mental stress and thus may be subject to a relatively high risk of chronic depression [29]. Therefore, it is important to alleviate or delay sensory damage with aging and to improve the independence and quality of life (QoL) of the elderly; thus, it is necessary to establish a residential environment from a healing perspective.

"Healing" can be defined as moving toward a healthy state through psychological, environmental, cultural, and social support based on experience, and it is distinguished from "curing", which recovers diseases through medical means [30]. From an environmental perspective, healing involves not only sight, but also various human senses such as touch, hearing, and smell, simultaneously, and space is recognized through multi-sensory reactions and experiences of mental and psychological changes such as emotional stability [30]. In the case of the elderly, a richer multi-sensory environment should be provided by weakening the sensory function of experiencing space, and many previous studies have emphasized the connection between nature and a healing environment for the elderly [31–33]. In the field of environmental psychology and neuro-architecture, the benefits of nature and how it affects individuals' health and well-being has been highlighted for centuries [34], yet now it requires more attention amid the increase of the aging population and population concentration in urban areas. Exposure to nature and natural analogs leads to positive rather than negative emotions and thoughts, and these changes have been demonstrated through responses such as blood pressure, heart rate, and muscle and brain activity [2]. Marcus [35] categorized natural healing effects into three categories. First is relief from negative physical and biological symptoms or at least relief from the perception of the symptoms. Continuous reminding of one's illness and pain can lead to a negative psychological state, and since nature stimulates the five senses to induce recovery through involuntary attention, aging-related symptoms can be alleviated [36]. Second is the stress reduction and recovery of cognitive function. The human brain responds to sensory patterns and elements found in the natural environment, and concentration and thinking skills are improved when humans interact with nature, and factors related to memory loss are suppressed [8]. Third is the improvement of awareness of well-being and satisfaction. As elderly people experience multidimensional aspects of aging, they have relatively low health-related consciousness, such as satisfaction with their subjective health status and quality of life, and they are more vulnerable to physical environments that negatively affect their health [37]. In other words, the conscious negative psychology arising from the individual's health and the surrounding environment can substantially contribute to the quality of life of the elderly through the connection with natural factors. This study emphasizes that the residential environment of the elderly should be planned with the intention of recovery and healing through the connection with nature as a physical measure to manage and prevent aging problems.

Table 1 shows the contents and results of previous studies that investigated the benefits of nature for the elderly. The effects of nature related to the health of the elderly vary physically, mentally, and socially and appear as physical function enhancement and recovery, psychological recovery, emotional satisfaction, and an increase in the subjective health and welfare index. In particular, horticultural programs such as plant cultivation and harvesting can serve as an economic motivator for productive activities in old age. The natural environment and elements covered in previous studies include not only direct-contact activities, but also indirect nature-inducing materials such as images and videos related to nature. The simulated natural environment showed a recovery effect similar to that of the real natural environment. The characteristics of natural experiences that contribute to the health and well-being of the elderly are direct and indirect views of specific landscape elements, such as green space and water, and various vegetation. This creates a multi-sensory environment that represents changes in nature, such as sunlight and shade, as well as the sounds of nature. It includes providing activities and environments that involve the communication with living organisms (animals and plants) in nature, while maximizing repeated access to experience these characteristics. This expands our understanding of how to experience nature and suggests the potential value of actively utilizing the benefits of nature in physical space.

Table 1. Health benefits of nature associated with the elderly.

Resource	Participants	Measurement	Outcomes	Health Benefits
[38]	Over 50 years old. *n* = 103	: Visit the park located in the city center for more than two hours a week for one year : Survey of natural factors and environment of parks and awareness of health and nature experiences (Likert scale 7)	: The higher the awareness of natural experience, the lower the level of anxiety about health, the higher the level of physical function, and the higher the preference for natural elements	Physical function enhancement/ psychological recovery/emotional gratification
[39]	62–93 years old *n* = 50	: Comparison of the survey results on the natural image of the non-elderly and the elderly/the elderly are divided into three groups according to their living environment, such as cities, rural areas, and facilities : Conducts a familiarity, preference, and resilience assessment of images in environmental categories: streets, cities, and natural environments, etc. (Likert scale 11)	: For all three groups of senior citizens, hill and lake images are considered to be more resilient, preferable, and the most familiar compared to residential, urban, and industrial areas : The correlation between preference and resilience is statistically significant in the elderly group	Psychological recovery/emotional gratification
[40]	Over 65 years old *n* = 61	: The experimental group is exposed to sunlight for about 2 h for 5 days : Measure the demographic status, physical condition (blood pressure and pulse, chronic disease), and PSQI of the elderly	: The sleep quality score of the experimental and control groups improved from 10.45 +/− 1.98 to 6.081 +/− 2.45 after exposure to sunlight ($p < 0.001$) : Strong positive relationship between sun exposure time and sleep time, regular sleep activity, and sleep state	Positive biorhythm and sleep quality
[41]	Under 79 *n* = 53	: Survey and in-depth interviews on subjective physiological and emotional responses to soundscape	: The closer the sound of nature, the more positive and preferred it is : Prefer the sound of birds and leaves, and recognize the sound of waterfalls, animals, etc., as pleasant sounds.	Emotional gratification
[42]	The elderly in Tokyo *n* = 3144	: Analysis of the correlation between the life expectancy of the elderly and the natural environment around their residence (for 5 years) : Survey on the conditions of living environment excluding social and economic effects of the elderly (self-response formula)	: The positive living conditions for the longevity of the elderly are the creation of parks and street trees, the absence of noise from cars and factories and the area and time of high sunlight.	Higher life expectancy
[43]	Adults and the elderly *n* = 30	: Participate in outdoor garden and indoor reading activities for 30 min after performing stress-inducing tasks (Stroop) : Repeated measurements of saliva cortisol readings and self-reporting assessments	: Both garden walks and reading activities resulted in a decrease in cortisol, but the garden walk group showed a much lower level of decline. : In particular, stress levels have fully recovered after gardening, but there are more cases of recital after reading activities.	Reduced stress/psychological recovery
[44]	Alzheimer's patient *n* = not presented	: Observation and investigation of behavioral disorder characteristics of Alzheimer's patients using closed gardens	: Patients visiting the garden show reduced behavioral disorders and reduced anger control behavior	Emotional/psychological recovery
[45]	Alzheimer's patient *n* = 28	: Monitoring medication type, dosage, falls, etc., according to the frequency of use of the patient's garden	: The number of falls and the severity of falls of older people with more frequent garden use decreased by approximately 30% : Significant decrease in anti-psychotic medication	Physical function enhancement/ psychological recovery

Table 1. *Cont.*

Resource	Participants	Measurement	Outcomes	Health Benefits
[46]	Average age 73 *n* = 193	: Preference analysis of green space characteristics in urban environments related to the subjective stress index : Accessibility and noise level of green park and preference for the presence of shade, ponds, aquatic organisms, etc. (visual discrete choice experiment)	: Prefer green space that is easily accessible and quiet and cool : The more shade, trees, and green spaces with ponds there are, the higher the preference.	Emotional gratification
[47]	A resident around a green space. *n* = 1347	: Conduct random selection and post-survey : Frequency of activities in green spaces by age, preference for characteristics of natural environment, WHO welfare index : Older = 55–65 (21.4%), 66+ (18.3%)	: Prefer spaces that nature-like/rich in species/lush/beautiful/varied : The higher the frequency of activities in green spaces, the higher the preference for natural environment characteristics and the WHO welfare index	Emotional gratification/ subjective health and welfare index rise
[27]	The elderly *n* = 28	: Survey on physical and mental effects of plant-based gardening treatment programs. : Participates in horticulture once a week for two months : Cortisol measurements and senior fitness tests for one week before and after the program ends	: The cortisol levels in the horticultural therapy group significantly decreased after horticulture activities compared to the levels before : SFT's 6 sub-check item scores have been greatly improved	Physical function enhancement/reduced stress

Note: PSQI = Pittsburgh Sleep Quality Index, SFT = Senior Fitness Test.

2.2. Biophilic Experience and Biophilic Design

2.2.1. Biophilia and Biophilic Experience

The relationship between nature and humans can explain humans' general preference for nature from an evolutionary perspective based on early geographic research. An individual's feelings and perceptions related to environmental preferences are based on the characteristics of places that are likely to overlook the landscape as well as places that you can discover resources or hide from dangers or threats [48]. Biologist Edward O. Wilson further advocated the theory of "biophilia" from an evolutionary point of view and has expanded this concept. Biophilia, which refers to human intrinsic affinity for life and natural systems, discusses the relationship between nature and humans based on the emotional alliance of humans inherent in natural life [1]. The goal of biophilia is to restore a healthy relationship between humans and the environment, and related studies have explored biophilia as a method to induce positive natural experiences, while offsetting negative environmental factors and creating a relaxed mental state [23,49].

Human indoor occupancy time is increasing, and for the elderly, social activity decreases due to aging and, in particular, retirement. Such daily life isolated from the outdoor environment cuts off positive experiences with nature and damages the relationship between humans evolutionary and instinctive characteristics with nature [17]. However, experiences with nature based on biophilia can provide a wide range of physical, mental, and behavioral benefits. Physically, these include reduced blood pressure, increased comfort and satisfaction, decreased disease symptoms, and improved physical health [2,35,45]. Mental benefits include satisfaction and motivation, reduction of stress and anxiety, and an improvement in problem-solving skills and creativity [8,36,50]. Furthermore, positive behavioral changes increase attention and social interaction, while decreasing hostility [23,44]. Therefore, informing a planning technique that enhances biophilia factors in indoor spaces is a research issue that should be addressed with great importance, as it can be a solution to various health problems.

Kellert and Wilson [1] argue that biophilia can be achieved not just by an instinct, but by complex learning rules and repetitive experiences that cultivate and factor in human biological tendencies. In other words, the biophilic experience cannot be replaced by physical concepts or objects such as architectural styles or advanced devices and technologies that have appeared in the process of the development of modern society; however, it can be appropriately expressed in a new environment that is conscious and artificial and continues in future generations [51]. This study focuses on the method and possibility of linking the positive natural experiences of the elderly with smart-home technology based on the biophilia learning rule, that is, the biophilic experience claimed by Wilson.

2.2.2. Biophilic Design

Biophilic design is a design strategy that aims to make modern living spaces suitable for promoting human health and well-being [8]; an applied science that aims to plan a physical environment that reflects the concept of biophilia. Biophilic design stemmed from sociology and ecology in the study by Kellert [8] and has been addressed in various fields such as psychology, medicine, and architecture since then. Biophilic design differs in characteristics and classification criteria depending on the relevant researcher and has been embodied in dimensions, elements, and attributes of biophilic design [8], patterns of biophilic design [49], experiences and attributes of biophilic design [23], and the biophilic quality index (BQI) [52]. Practical examples of biophilic design measurement criteria based on this are the Living Building Challenge (LBC) and the WELL Building Standard (WELL) in the U.S. The LBC is a certification system developed by the International Living Future Institute (ILFI), referring to six elements and 72 attributes of the biophilic design proposed by Kellert [53], and it requires a high level of environmental performance. The WELL Certification, developed by the International WELL Building Institute (IWBI), is the first certification system focused on human health and comfort. The criteria for measuring biophilia in this certification are addressed by the ”mind concept”, which emphasizes the improvement of users’ mental health through construction programs and designs [54]. Although biophilia is only one essential component, and there are additional points in obtaining certification, it is an important factor that has a unique impact on the project.

Kellert [23] emphasized the importance of the biophilic experience for practicing biophilic design and organized it according to nine biophilic design principles and three categories: Direct Experience of Nature, Indirect Experience of Nature, and Experience of Space and Place, all of which propose to help integrate the relationship between nature and human into the architectural environment. The details are shown in Table 2.

Table 2. Experiences and attributes of biophilic design by [23].

Direct Experience of Nature	Indirect Experience of Nature	Experience of Space and Place
Light Air Water Plants Animals Weather Landscapes View Fire	Images Natural materials Simulating natural light and air Naturalistic shapes and forms Evoking nature Information richness Age, change, and the patina of time Natural geometries Biomimicry	Prospect and refuge Organized complexity Integration of parts to wholes Transitional spaces Mobility and wayfinding Cultural and ecological attachment to place

The study by Kellert [23] underlines a set of options for enabling the biophilic experience in an effective way, replacing a limited checklist of options; these options can be appropriately and specifically applied to the presented experiences and attributes. In other words, the artificial environment pursued by biophilic design is not limited to indoor spaces, and new perspectives and meaningful attempts for appropriate and specific application methods are needed. Until now, previous studies related to biophilia and biophilic design have played a significant role in advancing our understanding of how the physical environment affects health and well-being; however, most of the studies have not considered the variety of smart methodologies and technical aspects of experiencing nature. Specifically, there is a tendency among them to overlook everyday places such as residential homes in modern society and urban environments [34]. This paper seeks a fresh perspective and an appropriate plan to enable the biophilic experience in smart-home technology and services, based on previous studies.

2.3. Residential Environment and Smart-Home Service for the Elderly

In recent years, the concept of "successful aging" has emerged, a concept that seeks methods for supporting multi-dimensional needs and possibilities for the elderly in social, psychological, and biological aspects to address such needs. In the past, spatial design, which originally focused on care facilities and medical centers for the elderly, has been expanded into housing and communities to support their daily lives [55]. In particular, among the methodologies for realizing successful aging, AIP, which involves getting older with familiar people in a familiar area, has important significance in the expectation that caring for local communities is cost-effective in terms of reducing financial burden [9]. Global aging and a change in the life consciousness of the elderly have had a significant influence across industries such as society, science, culture, and environment, and there is a consensus that focuses on having an interest in the residential environment of the elderly, which to date has been neglected in the existing welfare policy that supports AIP [56]. That is, the residential environment for the elderly is the key to realizing AIP; a positive, healthy residential space is crucial for their well-being and is needed for them to have a productive life. Lawton [57] argues that from a person–environment fit perspective, the life of the elderly varies according to the fit between the individual's situation and the environment, meaning that even within the same type of environment, people who are more vulnerable in terms of health, function, and resources are more affected by the environment than others. Therefore, elderly people must live in a place with environmental conditions that can promote their health and ability to function; thus, natural factors that can support the elderly's multi-dimensional health [38,39,43–47] should be applied to the elderly's residential environment.

These days, support for residential-based services has been developing so that elderly people can lead independent daily lives in the local community and live a prosperous life. As various innovative technologies are combined with urban infrastructure, the interest and demand for smart homes for the elderly are rapidly increasing. In addition, as housing is recognized as an important resource for elderly care, along with the AIP concept, providing services not only for health management but also for safety, convenience, and daily life support has become increasingly important. Smart homes refer to houses equipped with home networking technology and systems to improve the quality of life of the residents [58], and studies on customized smart-home service environments considering various social classes have been actively conducted recently. Previous studies related to smart homes for the elderly underlined self-sustaining and sustainable service environments, such as home automation and the convergence of home-appliance-based comprehensive living convenience, health care, resident management, and self-supporting residential systems [59–61]. In a situation where most smart-home environments consist of device–device and device–occupant interaction services, which centers on home appliances and individual devices, the interaction method of smart devices is related to the input/output method of information, thereby affecting the usability of the elderly [62]. This is true among various groups and is also closely related to spatial characteristics such as the shape and size of the devices, for example, how the devices are installed, etc. [63]. Therefore, this study considers the technologies that make up the smart-home service as well as the interaction characteristics of devices from the viewpoint of the residents, while also considering the spatial perspective, as shown in Table 3.

With respect to the interaction with the occupants, the contact type refers to control panels and switches that users use through direct interaction, while non-contact refers to sensors and receivers that perform their functions in the living environment of occupants without direct contact [64]. From a spatial point of view, non-contact is divided into mounted (M) and embedded, both of which require additional installation and attachment in the space; of these, the embedded type includes both space embedded (SE), that is, built into the spatial structure, and equipment embedded (EE) for which service-specific functions are included in the smart devices or intelligent devices replace existing ones [65].

Table 3. Interaction characteristics of the smart-home devices and equipment.

Type of Interaction		Characteristic
Resident	Contact	Requires direct interaction and physical contact with residents (touch screen, smart floor, etc.)
	Non-contact	To perform functions within the living environment without physical contact or physical manipulation of residents (automatic controller, luminance sensor, etc.)
Spatial	Mounted type (M)	Connect additional devices to control service functions or attach them to existing environments (attachment type sensor, remote controller, etc.)
	Space Embedded (SE)	Built into spatial structure, invisible (transparent switchable glass, smart windows, wall display, etc.)
	Equipment Embedded (EE)	Service-specific features are built into smart devices or replaced by intelligent equipment (mobile application, intelligent objects, social robot, etc.)

Smart-home services consist of sensors, controllers, actuators, displays, and other smart devices and systems as a network, enabling the localization and remote control of domestic environments as well as automation [62,66]. The home network gathers and stores data transmitted from the input device through the home gateway or platform and converts it into a single protocol to deliver it to the output device [67,68]. Smart-home services for the elderly aim to strengthen physical, mental, and social health management of the elderly and can be categorized into health monitoring (HM), environment monitoring (EM), risk management (RM), awareness improvement (AI), and community management (CM) [60,69]; details are shown in Figure 2.

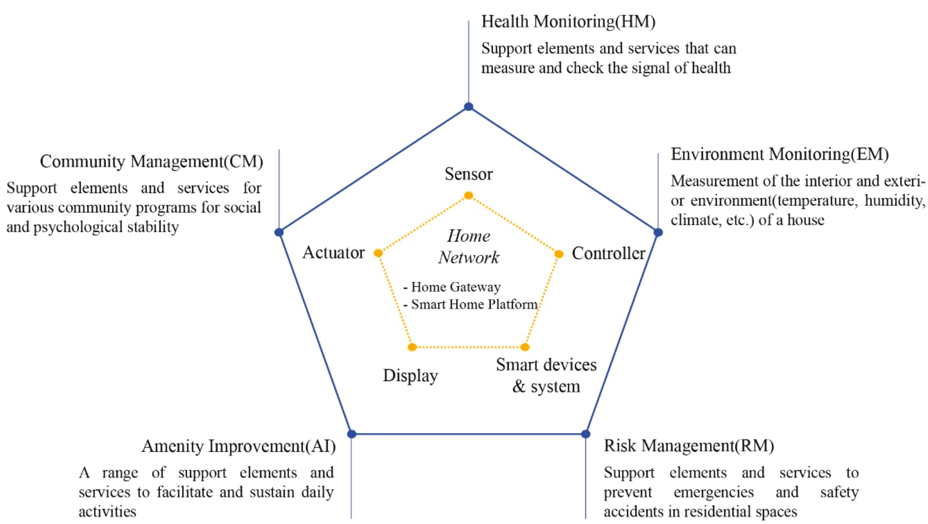

Figure 2. Smart-home service components and contents.

Smart-home technology is being used to support the various needs of the elderly, and the fundamental goal of all technologies and services is to improve the QoL of humans [60]. From this perspective, although smart-home services maximize the convenience and efficiency of housing for the elderly and families, it is often seen as a “mechanical utopia” rather than a high-quality living space. Up to now, smart homes for the elderly have focused on checking their health status in real time, responding to crisis situations as quickly as possible, and communicating more easily with medical professionals or family members [70]. Importantly, despite the continuing emphasis on experiences with nature in the residential environment of the elderly, discussions about applying it to smart technology or turning it into a service are insufficient. This stems from the perception that nature and smart-home technology are contradictory concepts; another reason is that smart-home-related research usually focuses on the modernization of existing smart-home service systems. However, the development of smart-home technology and its devices to date can be effectively used in contacting, controlling, and directing nature within the home environment, and the concept of biophilia based on the relationship between humans and nature could lead to a new trend in the smart-home industry; thus, biophilia must be considered. Therefore, the smart-home service for the elderly should focus on supporting a more multi-sensory nature experience and immersion in the experience by easing the limitations of the physical, regional, and geographical conditions, and should provide a high-quality residential environment by connecting nature and technology.

3. Services and Devices for a Biophilic Experience

This study has considered previous studies regarding smart-home services and technologies for the elderly to integrate technologies and services that support the elderly's experiences of biophilia in their homes. To systematically review smart-home services and technologies for the elderly, and support their experiences with biophilia, a variety of keywords were used, and in the case of the selection criteria for services and technologies, we refer to the analysis contents of Tables 1 and 2 specified in Section 2. Table 4 shows the details.

Table 4. Search strategy for literature review.

Analysis Framework	Contents	
Keyword	Elderly	"Aged", "Old people", "Aging population", "Senior", "Older adult"
	Services and technology	"Smart-home service", "Smart-home technology", "Healthy living", "Gerontechnology", "Biophilia technology", "Biophilic design industrial", "Indoor garden technology", "Ubiquitous technology", "Robotics", "IoT", "Automated home", "VR (Virtual Reality)", "AR (Augmented Reality)", "Immersive technology"
Criteria	- Does it contribute to the health and well-being of the elderly? - Does it support direct and indirect views in relation to specific natural environmental factors? - Does it support multi-sensory experiences of various changes in nature such as light, wind, sound, etc.? - Does it support direct and indirect communions with natural creatures? - Does it support experiences with natural ecosystems and systems? - Does it support accessibility for repetitive experiences of those features?	

The initial keyword search resulted in 45 duplicates out of 303 papers in six databases. After that, 124 documents were screened, excluding 98 documents that were judged to be inconsistent with the research topic and analysis criteria. After screening the final full-text review, 93 papers that did not meet the criteria were excluded, such as accessibility and application of housing and relation to nature or ecosystems. Finally, 41 papers were selected according to the eligibility criteria. Figure 3 shows the details of this procedure.

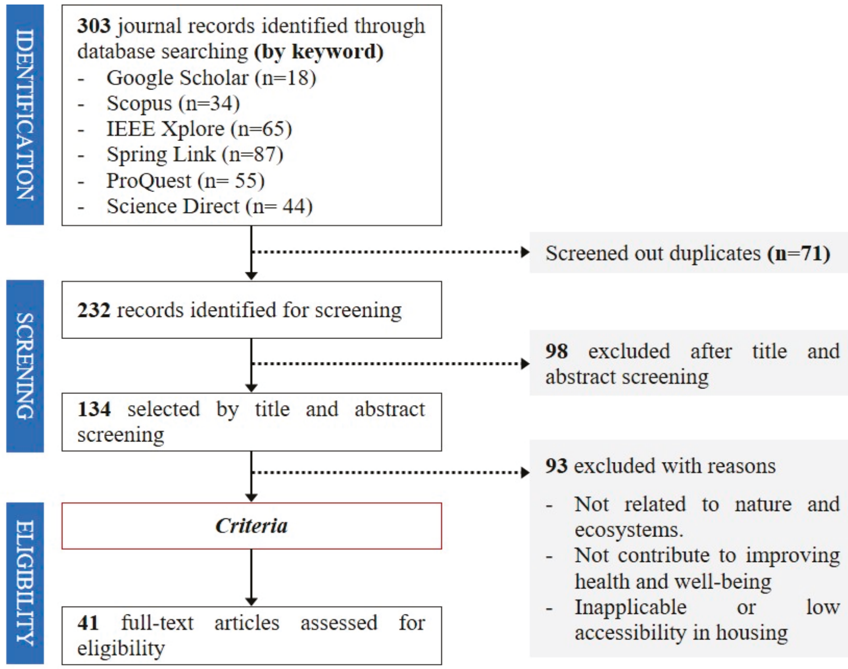

Figure 3. Literature review flow diagram.

Based on the literature reviewed, this study derived the types of smart-home services that involve experiences with biophilia according to Kellert's three categories of experiences [23], proposing sensors and devices according to the configuration of smart-home services.

3.1. Direct Experience of Nature

The direct experience of nature is fundamental to having experiences with biophilia, which represents an actual contact with the features and characteristics of the natural environment [23]. Lighting and air quality in homes, which are key factors that improve the quality of life, are already being provided by an environmental control system in the smart-home industry. However, existing environmental control systems that focus only on energy efficiency and convenience from a bio-friendly perspective need to provide us with experiences of natural light and air in a more diverse and creative way. Along with automatic opening and closing devices, supporting devices, such as louvers and reflectors that can track the sun's angle and its light direction (Heliostat Mirror) [23] and diffuse or transform it, are required to provide various light environments. In addition, a single home network should also be controlled so that the devices can achieve an optimal lighting environment. In particular, responding to weather conditions generating an awareness of changes in the seasons and weather can also be expressed as the potential needs of humans [71]; allowing users to see what is outside the building in real time gives them a sense of protection and understanding of nature. This includes collecting solar and rainwater and listening to the sound of wind or rain [23]. Communing with living things is another factor that induces us to have direct experiences with nature. Considering the results of previous studies, which found that spending time with companion animals and performing horticultural activities is beneficial to the mental health of the elderly and promotes their social activities [27,72,73], it is considered desirable to provide companion animals and an environment in which plants can be cultivated in the elderly's homes with smart devices and systems for easy management and care. As a relevant case, Japan recently developed an animal-shaped artificial intelligence (AI) robot to help alleviate the feeling of isolation and depression in the elderly, allowing them to interact with animals and receive comfort from them even without the biological care required of actual pets [72]. Indoor fish tanks are an effective way to observe living things and access water in the house, and using a smart aquarium based on IoT makes it possible for users to easily utilize the benefits of living things and water, such as water quality and food management, proper lighting intensity control, etc. [74]. A smart plant grower, a product developed for use in homes or small farms with the development of smart agriculture, can act as an artificial supply of light, moisture, soil, and temperature necessary for plant growth, helping to maintain the best plant conditions while spending little time and effort to manage it; this has recently resurfaced due to the increasing interest in indoor landscaping and food safety [75]. In particular, environmental control technologies regarding plants are mainly used to improve air quality, and with the recent development of the greenwall irrigation automation system (GIAS), which consists of low-cost microcontrollers, microprocessors, and applications [76] it has become possible to provide natural and comfortable air quality at a low cost. Table 5 summarizes the services and technologies that support direct experiences with nature in the house.

Table 5. Smart-home services for direct experience of nature.

Service	Devices and Sensors		Literature Source
All services	Environmental controller and actuator	Automatic controller and actuator (windows/louver/curtain/HVAC system/other smart devices and appliances, etc.)	[77–79]
Maximization of light	Environmental sensor	Luminance sensor	[77,80]
	Environmental controller and actuator	Heliostat/mirror	[23]
Pleasant air and thermal	Environmental sensor	Temperature/humidity sensor	[77,80,81]
		Air volume/direction sensor	[79,81]
		CO_2 sensor	[77–79]
		TVOC sensor	[77]
		Dust sensor	[77]
	Smart devices and system	Greenwall irrigation automation system (GIAS) [1]	[76]
Animals and plants	Smart devices and system	PC/mobile devices	[76,82]
		AI social robot (Aibo/Paro/NeCoRo)	[55,72,73]
		Smart aquarium	[74]
		Smart plants growers	[75]
View and weather	Environmental sensor	Video/mike outdoor sensor	[80]
	Smart devices and system	Rainwater harvesting system (RHS) [2]	[79,81]
		Three-dimensional (3D) surround speaker	[55]
		Smart glass	[55,83]

[1, 2] Most of the paper sources for the elements of smart-home devices were literature review papers. The terms of devices were attuned to maintain consistent terminology, and these were newly established in this study.

3.2. *Indirect Experience of Nature*

The indirect experience of nature refers to the experience based on an image similar to nature, natural analogs, or its characteristics and processes [23]. In modern city centers and buildings, where it is generally difficult to have direct experiences with nature, the development of technology plays an important role in expressing the characteristics of nature as if they were real. The indirect experience of nature is a part of certain patterns and processes that appear in the natural world, which include natural textures, colors and shapes, simulations of light and air, and the passage of time [23]. In relation to the biophilic experience, stimulation of the five senses is considered substantially important, and in particular, the health benefits associated with experiencing nature arise from the opportunity to perceive and observe them rather than performing direct activities [36].

Immersion technologies, namely VR and AR, are particularly effective in maximizing the biophilic experience and having experiences with nature through simulated VR and AR environments also enhances physical and mental health conditions similar to that of experiencing real nature [84,85]. The VR and AR for visual stimuli can be implemented through a head-mounted display (HMD), an eye glasses-type display (EGD), a hologram projector device, or a screen-shaped display and are separated into a FogScreen, a wall display, an invisible display, etc., according to the projection method [83]. Of these, the FogScreen is chemical-free and can safely come into contact with clothing and household apparatus, as it is an immaterial projection screen composed of fog and airflow [86]. It comes in two types—either it is a stand-bar type or it is ceiling-mounted, so that it is inexpensive and can form a self-sustaining system through interlocking with a dehumidification system. An invisible display is transparent through which light and users' eyes are transmitted, therefore it can realize realistic AR by reflecting their visual direction to match the synchronization between the physical object and the media [83]. Angelini et al. [87] developed a prototype of a multisensory interactive window for the purpose of supporting the elderly's view of the natural environment and family connection; it is an intuitive interface that allows them to interact with their desired objects at any time and place. In addition, the use of a surround-sound speaker with a smart display allows synesthesia and hearing to be stimulated simultaneously, and the sounds of birds, leaves, wind, streams, waterfalls, etc., can promote the recovery of the elderly; however, the extent of the effect may vary depending on the individual's preferences and circumstances, so that it is necessary to provide sounds according to the information and condition of occupants [88]. In particular, when simulating virtual objects in existing residential spaces, immersion and satisfaction are obtained through smooth interaction [85]. Thus, there is a need to consider a multimodal interface, such as an occupant's voice, gesture, touch, etc., as well as scanning 3D spaces. The LiDAR sensor, which can detect user location and motion, including the scanning of 3D spaces, can precisely track the indoor environment and daily life through laser beams without the need for video equipment, meaning that it has advantages in terms of protecting privacy and maintaining security in the house [89].

Another essential element in the indirect experience of nature is the change in nature over time. Users can experience it through light, darkness, and air flow appropriately simulated according to season and time, which is supported by smart lighting, an HVAC system, etc. In recent years, the artificial lighting (similar to sunlight) and an artificial skylight provided by a virtual sky, etc., have been developed to be applied to houses and facilities for the elderly [90], making it possible to create a natural light environment indoors through projector lamps that reproduce light reflected from water, sunlight through the branches, shadows, etc. [55]. Table 6 shows a smart-home service and technology for the indirect experience of nature.

Table 6. Smart-home services for indirect experience of nature.

Smart-Home Services	Devices and Sensors		Literature Source
All services	Resident sensor	LiDAR (Light detection and range) sensor (location, movement, activity, behavior)	[78,89]
		Multimodal sensor (voice, touch, gesture, etc.)	[62,82]
		Physiological sensor (sleep, pulse, etc.)	[60,78,82]
	Smart devices and system	PC/mobile devices	[60,62]

Table 6. *Cont.*

Smart-Home Services	Devices and Sensors		Literature Source
Virtual and augmented nature	VR/AR Display	Wearable display (Head mounted display (HMD), Eye glass display (EGD), etc.)	[73,85]
		Hologram projector	[55]
		Screen display (FogScreen, wall display, invisible display)	[83,86]
	Smart devices and system	3D surround speaker	[55]
		Smart window (multisensory interactive window)	[55,87]
Simulating natural light and airflow	Environmental sensor	Luminance sensor	[77,80]
	Environmental controller and actuator	HVAC (Heating, ventilation, and air conditioning) system	[60,81]
	Smart devices and system	Smart guide lighting	[77,80]
		Artificial sunlight	[23,90]
		Projector lamp	[55]

3.3. Experience of Space and Place

The experience of space and place discusses ways to build the ecological context of the architectural environment and the characteristics of the natural environment, focusing on the physical properties of space, from the perspective of biophilic design. The present study deals with the service of the biophilic experience through connection with a smart-home technology. This study focuses on the immersive experience in order to experience the characteristics of place in a positive natural environment, including various technical solutions that support the physical environment. The experience of space and place is based on the relationship between man and nature and can be made through place-based relationships and evolved human–nature relationships [8]. Place-based relationships are closely related to the ecosystem of the region where the occupants live. From the perspective of biophilia, the architectural system refers not to natural systems or a collection of resources, but a desire for cooperation between man and nature. The collection-to-collaboration approach provides beneficial advantages for both man and nature and enables the conservation of indigenous ecosystems as well as the integration of the local environment [91]. The "Latro lamp", developed by Mike Thompson, fulfills the interrelationship of photosynthesis and energy generation through the extraction of energy during the photosynthesis of algae in the lamp, requiring sunlight, CO_2, and water [92]. This is also related to biomimicry that understands and mimics the unique properties of photosynthesis. Phillips Design's "Microbial Home", a service that minimizes waste through periodic input/output systems, systematically creates a circular ecosystem for residential activities, such as supplying energy obtained from waste generated in each residential space to other residential spaces for electricity, etc. [91]. The "methane bio-digester" kitchen island cultivates bacteria by crushing food waste and the excrement from the "filtering squatting toilet" and collecting bacterial gas (biogas) used in built-in lighting and cooking equipment. The "paternoster", a plastic waste decomposition system that utilizes the enzymes of fungus, produces edible mushrooms through plastic decomposition products. These bio-friendly home systems can solve waste treatment and renewable energy issues, reduce the workload and maintenance costs in the elderly's homes, and increase occupants' perception of interdependence with nature by recognizing the ability and circulation system of nature in daily life.

Their evolved relationship with nature indicates a desire in humans to explore and discover the natural environment as well as an interest in all the complex processes of it [23]. Assuming that experiencing the natural environment "as is" can provide direct benefits to the health and well-being of the elderly, there is a need to make this accessible from anywhere, regardless of physical, spatial, or temporal constraints. In particular, human genetic instincts for the natural environment enable the biophilic experience both sensationally and neurologically through a properly simulated natural environment [93]. The immersive experience, which represents the fusion of sophisticated computer graphics technology, big data transmission technology, and various human-centered interaction technologies [94], can maximize the biological reactions of man to the natural environment and can be used anytime, anywhere through wearable devices, applications, etc. The immersive experience has begun to develop in the fields of games and entertainment, and in recent years, has been widely used in physical exercise, programs that help strengthen cognitive function, and tests of immersion, among others [55,95–97]. In addition, it can also act as a medium to promote the improvement of sensory and motor functions, perceptual ability, cognitive function, formation of bonds, emotional relaxation, etc. [55,85,98,99]. Rendever provides customized VR content for seniors in homes and senior living centers while providing them with various services, such as reminiscing about places, displaying the destinations they wanted to go, and experiencing the natural environment [100]. The elderly, facility officials, and their family members have shown a high level of satisfaction with this as it allows them to experience natural environments through immersive experiences and to interact with family and friends in real time in a virtual environment. As immersive content has been utilized in various fields, such as learning, medical care, and communication, various actuators capable of working with VR/AR devices have been developed [85]. A haptic actuator that supports tactile sensation allows users to more realistically interact with objects they want in virtual and augmented realities; they are becoming thinner and smaller and can be worn as a soft material such as clothing, rather than as mechanical equipment [101]. The immersive content for the biophilic experience needs to be carefully set up so it can accurately represent detailed and diverse natural environments, including famous landmarks, landscapes, major climates, and distinguishing animals and plants [23]. In addition, it is important to express the unique characteristics of specific ecosystems, such as mountains, valleys, forests, wetlands, etc., and an environment with abundant resources and opportunities should be created [19]. For immersive content for the elderly in the future, content for their physical and cognitive training, development of actuators for interaction, etc., can be considered by utilizing the abundant information, discovery, and motivational characteristics of the natural environment [73]. Table 7 lists smart-home services and technologies for the experience of space and place.

Table 7. Smart-home services for indirect experience of nature.

Smart-Home Services	Devices and Sensors		Literature Source
Nature-immersed contents	VR/AR display	Wearable devices (HMD, EGD, etc.)	[73,85]
		Screen display (FogScreen, wall display, invisible display)	[83,86]
	Smart devices and system	PC/mobile devices	[60,62]
		Haptic actuator	[85,101]
Collaboration system with nature	Smart devices and system	Smart kitchen and toilet	[82,91]
		Natural energy reproduction system (NERS) [1]	[91,102]
		Rainwater recycling system (RRS) [2]	[79,81]

[1, 2] Most of the paper sources for the elements of smart-home devices were literature review papers. The terms of devices were attuned to maintain consistent terminology, and these were newly established in this study.

4. Biophilic Experience Based Smart-Home Service Framework

4.1. Smart-Home Service Content for Biophilic Experience

Based on the literature analysis, this study derived the contents of the biophilic experience-based smart-home service, as shown in Table 8.

Table 8. Biophilic experience-based smart-home service contents.

Type of Service for Biophilic Experience	Service Contents	
Maximization of light	S.1	Adjustment of louvers and curtains according to the amount of sunlight and its direction
	S.2	Real-time tracking of sunlight paths and inflow of reflected light
Pleasant air and thermal	S.3	Induction of natural ventilation and airflows (wind) according to the wind volume and direction
	S.4	Automatic temperature/humidity control according to the weather
	S.5	Confirmation of indoor air pollution levels and automatic ventilation
	S.6	Greenwall automation management
Animals and plants	S.7	Provision of social robots in the shape of cats or puppies
	S.8	Automatic management of water quality and temperature, food, etc., in water tanks
	S.9	Real-time plant status confirmation and automatic management
View and weather	S.10	Provision of glass that occupants can remotely covert it to transparent one
	S.11	Provision of videos showing real-time information on external weather and conditions
	S.12	Rainwater collection and providing the sound of rain
Virtual and augmented nature	S.13	A virtual display window showing the occupants' desired natural scenery
	S.14	A skylight display showing a virtual sky
	S.15	Provision of simulation of seasonal environments according to climate and of natural sounds
	S.16	Provision of virtual water objects/sounds such as waterfalls, waves, etc.
	S.17	Provision of 3D virtual animal objects (bird, butterfly, dolphin, etc.)
	S.18	Indoor lighting control according to the simulation of virtual objects and background
	S.19	Provision of natural sounds according to the situation of occupants such as sleeping, waking up, eating, etc.
	S.20	Virtual natural wall patterns and textures that can be controlled
Simulating natural light and airflow	S.21	Provision of artificial sunlight according to the intensity of illumination
	S.22	Provision of various virtual light shapes and shadows
	S.23	Provision of HVAC controlled according to occupant status
Nature-immersed contents	S.24	Provision of VR/AR content that users can experience and travel the natural environment
	S.25	Provision of content for physical/cognitive training based on natural environments
	S.26	Virtual natural elements that respond to touches and gestures
Collaboration system with nature	S.27	Waste collection and natural disposal
	S.28	Natural energy reproduction and rainwater recycling

The present study identified 28 total biophilic-experience-based services, prepared in consideration of the support of direct, indirect, local, or regional experiences between the elderly and nature, based on the technologies and services proposed in previous studies. The maximization of light maximizes the amount and intensity of sunlight entering the room by monitoring the external environment through the heliostat and luminance sensors and through the interaction of the indoor environment controller and actuator according to the collected information. In order to achieve a pleasant air quality and a comfortable thermal environment, namely "Pleasant air and Thermal", indoor natural ventilation is induced through external environment monitoring; the HVAC system automatically adjusts the indoor environment according to the weather to respond to changes in the external environment.

Animals and plants create an environment in which they can communicate with living organisms in houses, supporting the elderly and easily managed. The service "View and weather" protects the privacy of residents, allows them to view the natural environment and improves their perception of the natural environment by providing weather information and rainwater collection information in real time. Virtual and augmented nature and simulating natural light and airflow are technical supports for the indirect experience of the natural environment, providing simulated natural elements using virtual and augmented reality and a more dynamic lighting environment and optimized air quality. Nature-immersion contents allow for self-immersion in a virtual natural environment, and physical and cognitive reinforcement training is possible using the empirical characteristics of nature. Immersive content has excellent interactivity with users and can satisfy both the visual, tactile, and hearing senses, simultaneously, allowing a multi-sensory experience of the relationship between nature and humans. Finally, the collaboration system with nature is based on the cooperation between natural systems and humans and supports the expanded experience of biomimicry. It is possible to recall the interdependent human relationship with nature and to further integrate the local environment and preserve the indigenous ecosystem by directly participating in the natural processing method or through the creation process of resources.

4.2. Framework of Biophilic Experience Services

Smart-home services can be configured in various types through a combination of various sensors and devices in the house and Internet of Things (IoT) devices. In order to configure a smart-home network, the following items are required: a home gateway, an IoT cloud, and a resource collaboration-based home platform [103–105]. Figure 4 shows the framework flow for a biophilic experience-based service.

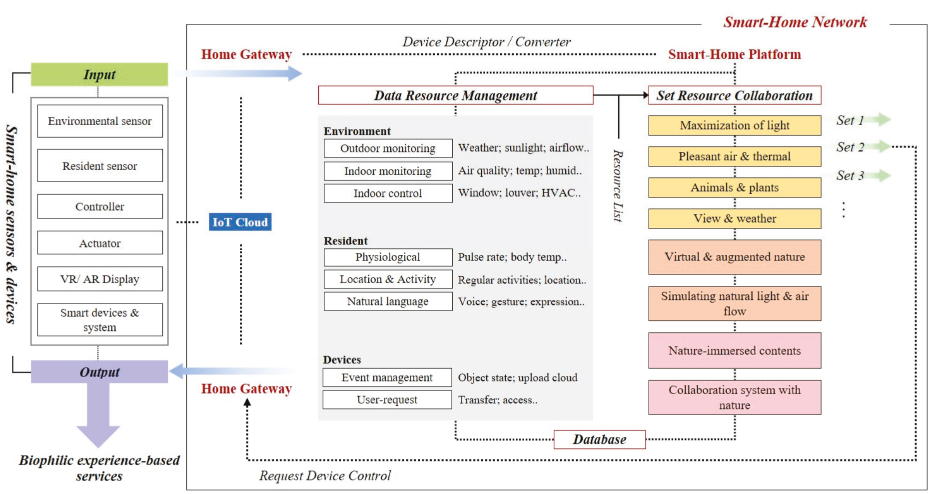

Figure 4. Framework flow for biophilic experience-based service.

Our proposed smart-home service framework uses sensors and devices that support the biophilic experience and IoT-based smart devices as service resources, while devices that can monitor and control status information in the house are used through a home gateway, and IoT-based devices are configured to be controlled through the IoT cloud. The smart-home platform manages device information transmitted through the smart gateway and each IoT cloud and converts and integrates protocols of all devices into resources for smooth service provision and collaboration [103,104]. The home gateway and IoT cloud mutually communicate, and all devices delivered to the smart-home platform through the home gateway are converted to follow the same protocol and classified into environment/resident/device resources according to their functions. Environment and residents are resources for environmental monitoring, environmental control, and resident information recognition inside and outside the house, and the devices are comprised of the resources used for the interaction with the IoT cloud to provide services that are input or output to IoT-based smart devices. The resource list is delivered to set resource collaboration (SRC), thereby making integrated control and additional collaboration possible by users or administrators. That is, once the SRC is completed, the data resource of the input device is defined accordingly, and all repeated processes are stored in the database of the smart-home platform.

This study organized the input and output devices that support the biophilic experience service according to the service framework, as shown in Table 9. Moreover, we proposed the interaction characteristics of smart-home devices from the perspective of residents and space, in consideration of efficient service provision and physical application in the house. From the perspective of residents, the interaction method was analyzed based on whether direct interactions such as physical contact and physical manipulation occur, and the spatial viewpoint is related to the shape of the device and the installation method in the space, so that the user can visually recognize the device. That is, the interaction is classified based on whether the device is attached to the existing environment, invisibly embedded into the space, or integrated in the form of a home appliance to replace the existing one (i.e., M, SE, or EE).

The interaction characteristics of smart-home service devices from the perspectives of residents and spatial considerations are referred to as contact-SE, contact-EE, noncontact-M, noncontact-SE, and noncontact-EE, excluding contact-M. Contact-SE are devices that require direct interaction by residents and are embedded in existing facilities or spatial structures, including smart kitchens and toilets for waste collection and disposal, smart windows with built-in touch screens, and wall displays. Contact-EE are smart devices or autonomous objects that require the physical manipulation of residents, including smart phones that provide remote control applications, natural language recognition, and social robots that can communicate. Noncontact-M are devices in the form of attachments and installations connected to IoT devices or remote control, including environmental monitoring, which performs functions on its own in the existing environment. These include devices such as heliostat sensors and mirrors, VR/AR screen displays, 3D surround-sound speakers, and home systems such as rainwater collection systems. Noncontact-SE devices automatically perform functions when events occur through environmental monitoring, such as indoor control devices and actuators, and are embedded into spatial structures such as windows, glass, and artificial sunlight. Finally, non-contact-EE devices, which are the most prevalent, are built into lighting and appliances for environmental monitoring, such as luminosity sensors, CO_2 sensors, and video/microphone sensors, and consist of various sensors and controls, such as a smart aquarium and smart plant growers.

In a prior study on the use of smart-home services by the elderly, the elderly responded positively to devices that are highly preferred for automated smart-home systems and are capable of intuitive interaction and physical manipulation [60,70,106]. Therefore, it is important to provide smart-home services from an integrated perspective. The way in which residents interact with smart-home devices should be adjusted according to the residents' physical and mental characteristics and should support cost savings and space efficiency through intelligent and smart devices that provide a variety of functions in place. The service-assisted devices and interaction characteristics proposed in this study distinguish active and passive use of residents by input and output devices and contribute to the search for physical methods of applying smart-home devices in the residential space.

Table 9. Interaction characteristics with input and output devices of service.

Biophilic Experience Services		Input Devices			Output Devices		
		Devices	Interaction		Devices	Interaction	
Maximization of light	S.1	Luminance/Heliostat sensor	Non-contact	EE/M	Controller and actuator	Non-contact	EE
	S.2	Heliostat/mirror	Non-contact	M	Window actuator	Non-contact	SE
Pleasant air and thermal	S.3	Air volume/direction	Non-contact	M	Window actuator	Non-contact	SE
	S.4	Temp/humid sensor	Non-contact	EE	HVAC controller	Non-contact	EE
	S.5	**CO2/TVOC/dust**	Non-contact	EE	HVAC controller	Non-contact	EE
	S.6	GIAS	Non-contact	EE	GIAS	Non-contact	EE
Animals and plants	S.7	AI social robot	Contact	EE	AI social robot	Contact	EE
	S.8	Smart aquarium	Non-contact	EE	Smart aquarium	Non-contact	EE
	S.9	Smart plants growers	Non-contact	EE	Smart plants growers	Non-contact	EE
View and weather	S.10	PC/smart phone	Contact	EE	Smart glass	Non-contact	SE
	S.11	Video/mike outdoor	Non-contact	EE	Screen display	Non-contact	M
	S.12	Video/mike outdoor	Non-contact	EE	RHS/3D surround speaker	Non-contact	M
Virtual and augmented nature	S.13	Smart window	Contact	SE	Smart window	Contact	SE
	S.14	PC/smart phone	Contact	EE	Smart window	Contact	SE
	S.15	Video/mike outdoor	Non-contact	EE	VR·AR Screen/3D surround speaker	Non-contact	M
	S.16	PC/smart phone	Contact	EE	VR·AR Screen/3D surround speaker	Non-contact	M
	S.17	PC/smart phone	Contact	EE	Hologram projector/EGD	Contact	EE
	S.18	VR/AR screen display	Non-contact	M	Smart guide lighting	Non-contact	EE
	S.19	Physiological sensor/LiDAR	Non-contact	EE	3D surround speaker	Non-contact	M
	S.20	PC/smart phone	Contact	EE	Wall display	Contact	SE
Simulating natural light and airflow	S.21	Luminance sensor	Non-contact	EE	Artificial sunlight	Non-contact	SE
	S.22	PC/smart phone	Contact	EE	Projector lamp	Non-contact	M
	S.23	Physiological sensor/LiDAR	Non-contact	EE	HVAC system	Non-contact	EE

Table 9. *Cont.*

Biophilic Experience Services		Input Devices			Output Devices		
		Devices	**Interaction**		**Devices**	**Interaction**	
Nature-immersed contents	S.24	PC/smart phone	Contact	EE	HMD/EGD, haptic actuator	Contact	EE
	S.25	PC/smart phone	Contact	EE	HMD/EGD, haptic actuator	Contact	EE
	S.26	Multimodal sensor	Contact	EE	HMD/EGD, haptic actuator	Contact	EE
Collaboration system with nature	S.27	Smart Kitchen/toilet	Contact	SE	NERS	Non-contact	M
	S.28	NERS/RRS	Non-contact	M	Lighting, smart plants grower, etc.	Non-contact	EE

Note: M = mounted type, EE = equipment embedded type, SE = space embedded type.

5. Conclusions

This study has suggested a smart-home service framework for the biophilic experience by analyzing previous studies related to smart-home and smart-technology cases that support biophilia. It also provides a theoretical basis for integrating the biophilia concept with the smart-home environment. The conclusions of this study are as follows:

First, when the urban environment is cut off from nature it can degrade human biological capacity, resulting in everyday life becoming more psychologically debilitating. Thus, measures are needed to actively provide the benefits of nature in homes for the healthy aging of the elderly. Previous studies related to biophilia and biophilic design have systematically developed physical planning measures for health, but constraints of local and urban planning tend to overlook day-to-day places in modern society and urban environments [34]. The results of a prior study examining human positive responses in simulated natural environments suggest the potential of smart homes and IT technology for biophilic design [20–22].

Second, the biophilic-experience-based smart-home service proposed in this study was derived from the analysis of the direct, indirect, place, or regional characteristics of the positive biophilic experience for the elderly and the technical factors of the smart home that support it. Smart-home services for the elderly's biophilic experience can be provided through existing smart-home technologies, such as environmental monitoring and control, lighting technology, and home smart devices. However, the purpose of the service must be focused not only on energy efficiency, but also on the exposure to nature according to different situations of residents. In addition to providing energy information for buildings, service resources are needed to deliver weather information and natural soundscapes outside the house. In addition, it is necessary to expand the scope of VR and AR technology and immersive content and use them as a means of natural immersion experience that is free from spatial and temporal constraints, not just a means of providing information. In the case of a home system, it is necessary to develop a cooperative relationship with nature, providing new values of sustainable residential spaces from the perspective of the Green New Deal.

Third, this study proposed a biophilic-experience-based service framework and interaction characteristics for the application of input and output devices and services accordingly. In this study' s smart-home service framework, sensors and devices that support a biophilic experience and IoT-based smart devices are used as service resources, and collaboration within resources is possible through a home gateway and an integrated home platform. Specifically, as a result of analyzing the characteristics of the interaction with smart-home devices from the perspective of residents and spatial considerations, it is necessary to consider the reduction of the device implementation cost and space efficiency through resource integration and collaboration according to the interaction method and function.

This study underlines that smart-home technology should reinforce the experience with nature for a sustainable living environment for the elderly; it also identifies methods that link the biophilic experience with smart-home technology. In this process, it is meaningful in that it organized the existing literature and evidence and suggested a smart-home service and utilization plan from a new perspective. Planning techniques that reinforce biophilic tendencies in indoor spaces can be a solution to many health problems of the elderly, but previous studies related to smart homes for the elderly have focused on the treatment and management of diseases, emergency response, and convenience of the elderly rather than providing sufficient support for positive experiences of the elderly in houses or for rapport with nature. In addition, since studies linking the biophilic experience with smart technology and services in the field of biophilic design are insufficient, this study is unique in that it offers a new perspective for enabling the biophilic experience.

This theoretical contribution broadens the understanding of how to experience nature from the perspective of a sustainable residential environment. Moreover, it has value in managing positive experiences and maintaining a high QoL in the elderly in smart homes. In particular, the biophilic experience-based smart-home services content proposed in this study informs the expansion of the aged-friendly smart-home industry and contributes to the development of smart-home services along with new service trends. Finally, this study contributes to the consideration of improving the physical applicability of devices in smart homes and the composition of resource collaboration of devices for each service by proposing the interaction characteristics of input and output devices according to the service framework, residents, and spatial perspectives. As the biophilic experience service and framework of the study utilizes the limited case category of previous studies included in the literature review, one limitation of this work is the presentation of a clear criteria between certain items in the range of analysis results and the suggestion of interaction characteristics. This is because there are cases in which the definition of a single analysis criterion is vague because of the diversification and complexity of the contents of services; however, this study is meaningful in that the service plan has taken a holistic approach to services and devices, occupants, and spaces. In particular, device type and interaction method are related to the physical factors and usability of the installation method, as they can be used in related research fields. In further studies, the quantitative data will be analyzed using a clear and rigorous methodology, and the search criteria will be expanded. In particular, for the implementation of the framework suggested in Figure 4, it is important to consider technical alternatives and specific implementation methods, and to proceed with convergence studies that take them into account. Overall, it is necessary to provide further suggestions for ways to alleviate the restrictions and limitations on the use of smart-home services for the elderly. It is also crucial to gauge the importance of the elderly's biophilic experience services in the house, considering the elderly's satisfaction and physical and cognitive functions.

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Visualized Co-Simulation of Adaptive Human Behavior and Dynamic Building Performance: An Agent-Based Model (ABM) and Artificial Intelligence (AI) Approach for Smart Architectural Design

Hwang Yi

Architectural Design & Technology Lab, Department of Architecture, School of Engineering, Ajou University, Suwon 16499, Korea; hwy@ajou.ac.kr; Tel.: +82-31-219-2493

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Abstract: Human (occupant) behavior has been a topic of active research in the study of architecture and energy. To integrate the work of architectural design with techniques of building performance simulation in the presence of responsive human behavior, this study proposes a computational framework that can visualize and evaluate space occupancy, energy use, and generative envelope design given a space outline. A design simulation platform based on the visual programming language (VPL) of Rhino Grasshopper (GH) and Python is presented so that users (architects) can monitor real-time occupant response to space morphology, environmental building operation, and the formal optimization of three-dimensional (3D) building space. For dynamic co-simulation, the Building Controls Virtual Test Bed, Energy Plus, and Radiance were interfaced, and the agent-based model (ABM) approach and Gaussian process (GP) were applied to represent agents' self-learning adaptation, feedback, and impact on room temperature and illuminance. Hypothetical behavior scenarios of virtual agents with experimental building geometry were produced to validate the framework and its effectiveness in supporting dynamic simulation. The study's findings show that building energy and temperature largely depend on ABMs and geometry configuration, which demonstrates the importance of coupled simulation in design decision-making.

Keywords: architecture; building performance simulation; performance-based design; agent-based model; Gaussian process

1. Motivation and Background

1.1. Performance-Based Design and Challenges

In recent years, a heightened awareness of energy and sustainability in built environments has remarkably changed the ways in which we design, construct, and think about building. A number of collective commitments to account for energy efficiency and high performance in architecture have fostered significant progress in terms of building production concepts, manufacturing, and detailing. In this architectural shift, the development of digital tools incorporates computerized performance simulation into the design process [1,2], which plays a vital role in bridging the conventional divide between design and engineering in architecture. Yi and Yi [3] proposed an automated optimal three-dimensional space layout framework coordinated by performance simulation and simulated annealing. Lin and Gerber [4] suggested the use of a multi-objective genetic algorithm and performance simulation for generative building form-making workflows. The visualized representation of energy data, building geometry overlaid with colored radiance intensity, and the interoperability of thermal information and design workflow help architects to better understand the thermodynamic mechanisms of building systems and the active engagement of design in performance improvement.

By definition, simulation is the virtual execution of a model that engineers abstraction to specify the hierarchical structures or properties of physical reality [5]. In architecture, building performance simulation (BPS) can provide analytical insights into environmental design fitness, yielding predicted outcomes with a series of numerical data. Moreover, the BPS does not only provide the functional utility of scientific analysis but also offers sources of advanced architectural design. Simulation data can unveil hidden dimensions of design parameters and organize design vocabularies based on sustainability principles. Thus, this simulation-oriented design approach, so-called performance-based (or performance-driven) design (PBD), can help architects to conceive of building design as a successive process of informed decision-making. Recent developments in PBD-integrated building information modeling (BIM) have uncovered the possibility of creative design guidance in terms of morphological generation and allocation of various building elements. This refined process of sustainable building design emphasizes intelligent architects' orchestration, coordination, incorporation, and prediction of environmental factors in their work of form-making [6].

Nevertheless, it is not always possible to use PBD to rigorously maximize the performance of every inch of a building. In effect, BPS is a mathematical algorithm that emulates the real world. It must deal with a complex set of energy formulas and thermodynamic variables; thus, PBD inevitably produces some uncertainty in design parameters, scenarios, and geometry [7,8]. For example, (1) at the early design phases, many simulation input parameters (efficiencies of fan and motors, system sizing parameters, operation schedules, etc.) are largely approximated; (2) available weather files, remotely obtained from past observations, do not clearly represent local weather or surrounding microclimates; (3) in BPS modeling, uncertainty arises according to the way in which thermal zoning is configured [9], and complex geometry representation such as the non-uniform rational basis spline (NURBS) is not recognizable to building energy simulation (BES). For these reasons, BPS has some issues of diagnostic uncertainty and is sometimes unable to reveal design alternatives. Additionally, the opacity of the BPS workflow has significantly hindered the widespread use of PBD in architecture. Therefore, the application of conflicting simulation data must be properly and selectively addressed for the effective evaluation of competing design candidates. For conceptual or schematic design stages with insufficient building information, the PBD process must be as efficiently functional and supportive as possible to quickly guide architects in finding optimal design solutions.

1.2. Co-Simulation: Design-Oriented BPS Platform

Although the uncertainties of PBD may be unavoidable, we should try to close the gap between simulation and reality—or even create more realistic virtual outcomes than reality—by leveraging tighter data networking of heterogeneous datasets generated from different sources or introducing high-level computational control of simulation processes. In this attempt, preliminary data can be collected to localize environmental inputs while missing information can be estimated using the appropriate statistical methods or machine-learning techniques [8].

In terms of PBD, building is a highly complex and engineered environmental system; therefore, it is very challenging to evaluate all performance criteria simultaneously. The core engines of BPS are specialized for different purposes and require an understanding of heterogeneous algorithmic procedures. Thus, the use of a single simulator provides partial information. Co-simulation is a holistic approach that can overcome this issue via the modular composition of different simulators or the hybridization of algorithms [10].

Co-simulation is not a new idea. There have been many efforts to combine heterogeneous BPS components, subsystems, and algorithms towards a unified simulation scheme, and several techniques to exploit the interoperability of multiple simulations exist in the context of PBD processes [11–13]. Hansen [11] first attempted to synchronize computational fluid dynamics (CFD) and energy simulation based on the Gauss–Seidel feedback pattern. Wetter [12] developed a software environment named

Building Controls Virtual Test Bed (BCVTB) that can activate user-driven external intervention in the simulation process. Hong et al. [13] suggested a cyber-physical system programming method based on the functional mock-up interface (FMI) that can be used in building information modeling (BIM).

The most straightforward of these techniques involves running existing simulators successively and making follow-ups on demand. This is more advantageous than real-time processing, but this method can become inefficient if it requires high-level expertise to interpret information and extra elaboration to put together different types of data in every iteration. An alternative approach is to create a design simulation platform, a sort of virtual environment enabling a collective exchange of data, models, criteria, and decisions based on a standard protocol for simulation interoperability. This does not intend to bifurcate the architectural process into design and analysis but rather to integrate information exchange through multipath input/output (I/O) control systems. This approach has the potential to widen the horizon of BPS' roles and functions extensively, increasing the flexibility of individual expert domains.

For architects and early-stage PBD, a co-simulation platform must serve to enhance design pursuits and PBD's process-driven workflow, where visual narratives of design and simulation become a design product. However, two major issues arise in this scheme: data synchronization and the development of information feedback loops. BPS is often overwhelmed by large quantities of data streaming, and design decisions may be misleading unless system models are appropriately defined. Excessively complex procedures to preprocess/refine building data may significantly delay the prototyping of design alternatives.

The resolution of performance analysis must be uniquely adjusted to intensify design power. Additionally, the organized reduction of complex variables to a set of parameters is necessary to quickly feed calculation results. These tactics must be able to synchronize all data flows in a unified automation process; thus, mathematical algorithms, data analytics, and parameters are blended in design pipelines.

Similar design-integrated approaches to PBD have been studied under the names of building information modeling (BIM) and computer-assisted design (CAD) systems [14–16]. However, most existing studies employ design simulation to retrofit existing buildings rather than to create new buildings from scratch. Funneling large amounts of data in different formats and streamlining algorithms and simulation engines into a few select design parameters as design agents are key in seamlessly interweaving design automation, rapid simulation, and optimal decision-making. The successful regulation of a synchrony of simulators through an agent-based architectural platform is promising for iterative PBD analysis and solution-seeking. Detailed performance analytics can enable the unified and rapid interconnection of design and analysis.

1.3. Agent-Based Model (ABM) for PBD

Known also as agent-based simulation (ABS) or individual-based modeling (IBM), the ABM is a computational method for modeling and analyzing complex systems and processes such as cellular structures, human cognition, or market networks of suppliers and buyers. "Agent" is anything that refers to a discrete model entity (or a rule/attribute-based actor) involved in changing a system's organization, appearance, or phenomena [17]. Based on system design, this could be a single person, a cell, a product, or any other entity engaged in system dynamics [18]. Each agent operates in a system with specific attributes and behavioral rules. ABM is a bottom-up approach because it is usually employed to examine overall system change by configuring autonomous individual actions and agents' decisions at a microscopic level. In particular, if a governing function or norm-authorizing system control is unclear and difficult to observe, this approach provides an effective solution to examine the collective impact to a system as a whole.

An ABM is comprised of three components: (i) agents (humans), (ii) a set of rules defining agent behavior, and (iii) a set of model setup parameters (a framework for simulation). Each of these is interrelated to assist in the construction of different model layers or a network of functional modules. In this regard, ABM is a very natural representation of a real system because actual, real-world phenomena are often convoluted, heterogeneous, and challenging to define with some regulatory parameters.

ABM has been applied widely across various areas, e.g., biology, urban planning, social science, and economics, to name a few [19,20]. In architecture and related areas, the ABM or agent-based approach benefits simulating human–building interactions, as it is able to deal with many arbitrary interventions engaged in dynamic behavioral relationships in terms of the effect-to-cause reasoning [21]. Lee and Malkawi [22] proposed a multi-agent model framework of energy-conscious building occupant behavior, and space syntax analysis (SSA) coupled with human agent simulation was found to be effective to characterize the interaction between human behavior and the physical setting of built environments [23,24]. Nevertheless, it is still challenging to incorporate ABM seamlessly into the architectural design process, especially in terms of the generative design of performance-based adaptive building geometry. It is noticeable that Gao and Gu [25] suggested agent simulation at a building level, and Andrew et al. [26] attempted to model spatial occupant behavior in a building plan regarding artificial lighting control. However, in most building studies, use of ABM targets the application of mechanical systems and energy use. SSA is mainly adopted on urban scales, exposing some limits in that it supposes completely purposive human movements and their complete knowledge of where they traverse in a static environmental context [22,24,27]. There are few or no ABM studies that attempt to address architects' concerns about PBD, i.e., generative geometry design, dynamic performance simulation, and visualized representation of process and outcomes [28].

2. Simulation of Human Behavior and Adaptive Geometry

2.1. Simulation of Human Behavior in PBD

Human behavior is a moving target for architectural design and among one of the most immediate yet uncertain factors in PBD. Thus, many researchers have worked hard to incorporate behavioral influences and parameters into design and analysis. For instance, the work of Breslav et al. [29] presented a visualization of occupants' spatial movements as well as their perception patterns through digital building modeling. Nagy et al. [30] leveraged crowd simulation techniques and space syntax to develop a generative space layout method. Moreover, there is growing recognition in the study of BPS that occupant behavior is a dominant component of building energy use [26,31–33].

Unfortunately, owing to the gaps in research between the fields of architecture and engineering, few PBD studies focusing on a unified approach to human behavior for both design and simulation have been published. Although there has been significant agreement on the need for behavior-centric approaches to building sustainability in architecture [34], human behavior has yet to be fully elucidated in the practice of PBD. Architects primarily seek to represent human activities and their spatial positioning graphically, and their impact on building energy and thermal comfort has not been fully explored via simulation. In contrast, on the BPS side, only the operation schedules of mechanical systems account for human behavior. Engineers focus on non-visual and numerical representations of occupants, which requires a certain level of scientific expertise. At any rate, an adaptive behavioral response to improve thermal comfort and the variability of space geometry to environmental changes has not been fully considered for the general performance assessment process and formal design development.

Therefore, human behavior modeling for PBD raises cross-disciplinary issues. PBD should be extended to be able to associate behavior-driven building system operation with geometry design and space allocation. Although it is challenging to predict bodily motion due to its random (unreasoned) nature, some habitual behavior scenarios of indoor space use can be established based on a situation-specific survey (of occupants' preferences, energy consumption patterns, and so on) for the purpose of design simulation. At the same time, the ambiguity of quantitative modeling must be clarified with performance-related behavioral definitions so that PBD results regarding sustainability are not biased.

2.2. Visualized Simulation of Adaptive Building Geometry, Design Automation, and Optimization

Generative adaptive form-making in PBD should be fueled by a clear strategy to build up robust data feedback for design automation and optimization. Performance criteria, environmental constraints, and design criteria must be coherently programmed/scripted in a visualized parametric design simulation framework [35,36]. For the full integration and automation of this framework in architectural design practice, this study employs the visual programming language (VPL) of Grasshopper (GH) for Rhino® (Robert McNeel & Associates, USA), which is among the most popular and widely-used pieces of digital architecture software, to configure an automatic form-making process driven by BPS and optimization. Using this tool, adaptive design candidates are populated using built-in GH components and Phyton (IronPython) scripts, according to a predefined optimization convergence rule and fitness that represent BPS results. The VPL-based PBD offers a flexible design simulation mock-up for both architects and analysts because their functions and systems can be customized as necessary and compiled to create new language components. GH-VPL modules with scripted feedback loops to control data flow can offer a synchronous workflow of geometry modeling, simulation, and optimization. Results can then be used promptly to update design solutions and performance analysis reports. For large projects with heavy computational loads, data storage can be aided by sharing cloud servers, data networking, or adopting parallel computing techniques. Recent developments of GH-VPL provide an advanced programming environment through the Python editor, and scientific data processing techniques served by Python libraries and packages, such as multi-objective optimization or machine-learning algorithms, can be adapted to visualized design process, which will eventually make the design process more intelligent and produce high-quality PBD solutions.

3. Materials and Methods

3.1. Scheme of PBD Automation

Figure 1 represents the early-phase architectural PBD framework proposed in this study. This scheme features an experimental design simulation integrated environment to support virtual real-time energy monitoring and reporting of BPS results. The developed computational platform is targeted at an initial phase of architectural projects, where users (architects) need to rapidly compare different building forms. Users can visually identify how dynamic formal changes of space potentially influence human behavior (space occupancy) that is actively engaged in energy-efficient operation and, conversely, how they work to optimize building forms interactively. This framework intends to support flexible and user-friendly building design practice through VPL, enabling the immediate visualization of the evolution of building geometry and behavior. Based on this workflow, GH-VPL can be further customized for different occupancy scenarios. In the suggested workflow, ABM and the artificial intelligence (AI) of the Gaussian process offer an algorithmic solution for behavior modeling that ensures the uninterrupted involvement of heterogeneous data sources in the streamlined form-finding process (Figure 1).

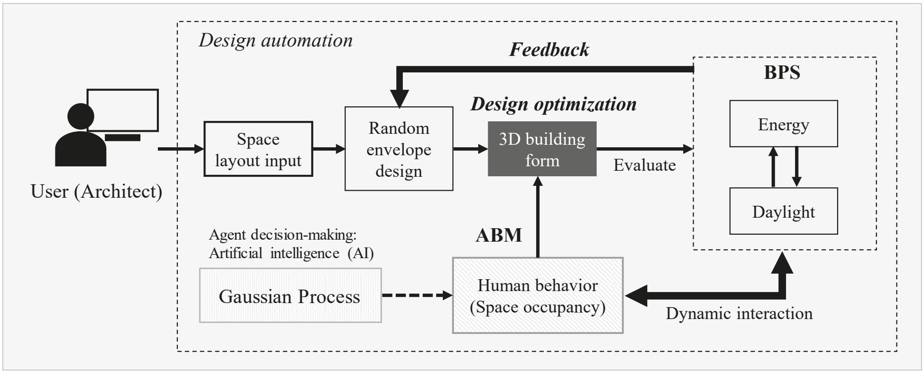


Figure 1. Scheme of ABM-based PBD automation process.

3.2. Development of a Visual User Interface (VUI)

The VUI was made with a VPL and GH and integrated with a BPS engine, EnergyPlus (EP), and an ABM model (Figures 2–4). It features a dashboard, geometry generation component, and integration of AI modeling using Python. The GH, one of the most popular VPLs in architecture, provides a graphic icon editor for the parametric building design process. Since this is a plugin of the CAD tool that supports complex geometric manipulation, it enables the design-oriented modeling of complex building systems as well as customized specification of the form-making process according to parameters set by designers. It also makes it possible to establish a seamless comprehensive model of computation through the co-simulation of a number of distinct analysis tools. However, despite such GH versatility in tool integration, it essentially offers a single option when it comes to data flow control. A scripted process is executed a single time through a synchronous data pipeline whenever an input parameter is available. To facilitate data-loop communication and multithread processing among different modules, a data flow director was coded using Python. This data flow director can control data connection and pathways by scheduling the rate of exchange. Data from external programs are stored in a CSV format, and the director commands an input module indicating when and how to read the data.

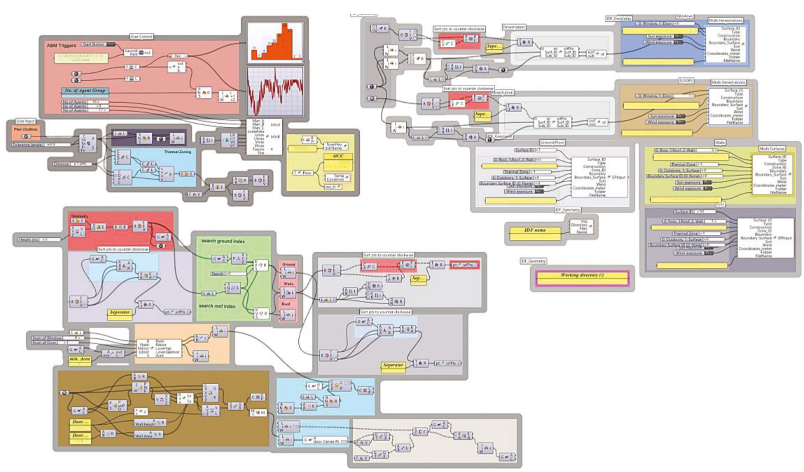


Figure 2. The whole VUI.

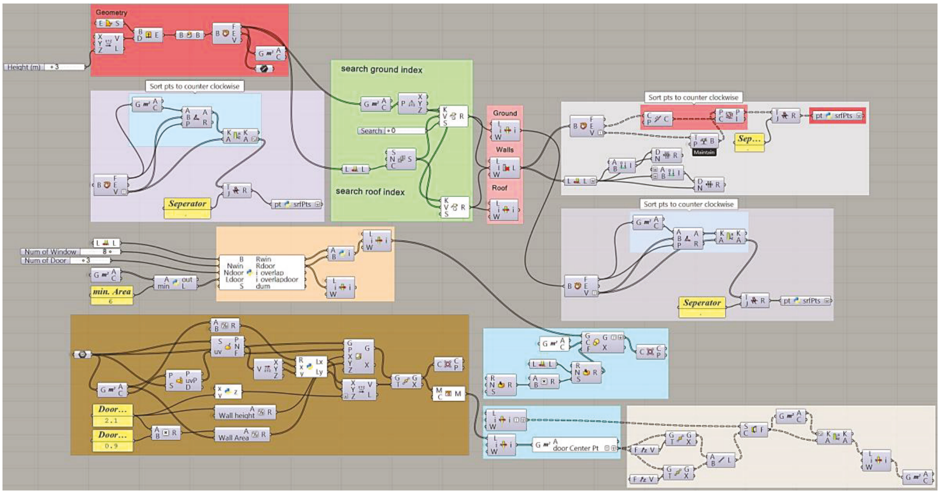


Figure 3. VUI: geometry generation and ABM component.

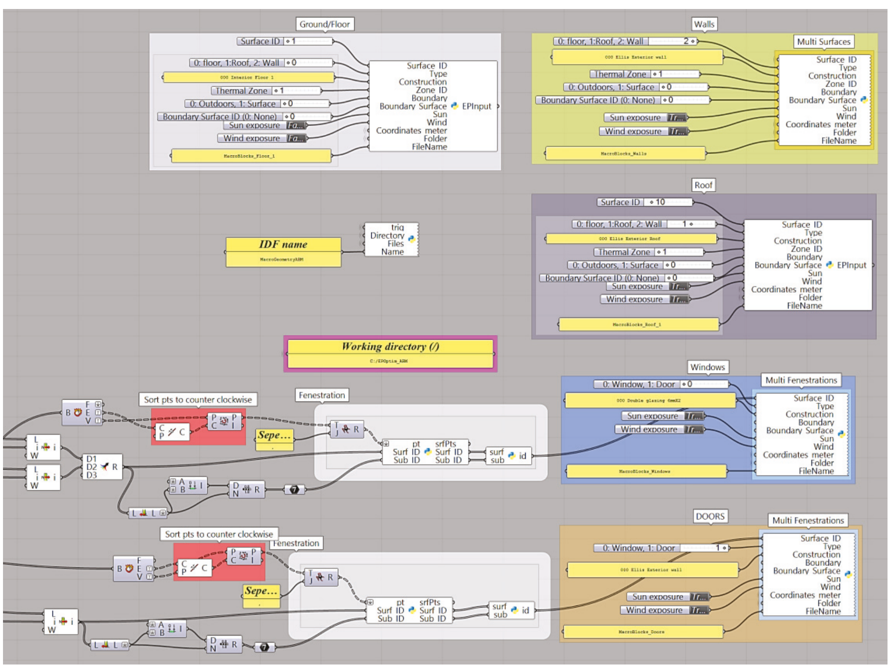


Figure 4. VUI BPS component: conversion of geometry data to EP format and writing an EP input file in *.idf*.

BPS coupled with automatic form-testing is used to evaluate energy use and daylight space in buildings. Although it is a critical component to gain environmental information on occupant feedback, there is a significant limitation in the use of EP for this purpose because EP's basic simulation setting is inflexible. More specifically, it runs all the way through once a simulation begins according to the initial setup. Thus, it informs design only once when each simulation run is done over a specific period, not responding to parameter variation during each time window.

EP supports external intervention on some simulation parameters while in a run through an extended setting. Accordingly, the BCVTB was encoded in this VPL interface (Figure 2). Once the user draws a curve or a polyline in Rhino as a building footprint outline, which is the most primitive input in the earliest design phase, the interface recognizes it. A building form generated with random fenestration (windows and doors) over exterior walls is converted to an EP geometry input format. Then, the script automatically triggers EP simulation and BCVTB. This initialization generates human figures in different positions, and the process visualizes the adaptive evolution of a building form and occupant behavior to optimize the form and energy use. Finally, a graphic dashboard is installed to present real-time simulation results.

3.3. ABM Development for Space Occupancy and Cognitive Agent Behavior

In this study, agents represent rational human building occupants that randomly belong to one of three social categorizations, Group A, B, and C, and each agent group has its own behavioral characteristics according to predefined attributes influencing energy-related building operation and room occupancy.

The studied ABM consists of four behavior-response modules: (i) social cognition, (ii) thermal response, (iii) positioning in space, and (iv) reaction. An agent's attributes are represented in two different condition-action (RA) layers that respectively characterize (i) preferences in terms of room occupancy and social interactions and (ii) thermal sensation and controllability. For the first RA layer, the following set of specific agent rules (*R.1~R.6*) is set to program agents' cognitive behavior.

(R.1) Most agents in Group A like to stay around corners.
(R.2) Group A and B have an affinity with each other. Agents in these groups would stay around together.
(R.3) Group B would not like to stay with C.
(R.4) Most agents in Group A prefer to stay inside in the morning (7 a.m. to 12 p.m.).
(R.5) Most agents in Group B do not like to stay around doors.
(R.6) Most agents in Group C prefer to stay around windows.

Agents think, act, and decide based on these reflex rules. Basically, they are self-cognitive, but those within the same group are not supposed to communicate to one another. Individual decisions of agents made by the condition-action rule take on collective behavior in space. For mathematical modeling, we find that the rule definitions involve some ambiguity in their language, such as "most" or "prefer". It is almost impossible, admittedly, to specify different personal preferences or mindsets uniformly without any uncertainty. That said, to make this design experiment as scientifically rigorous as possible, some rules are described with probabilistic formulas in ABM encoding. Assuming that a degree of compliance with the rules is normally distributed, our belief in specific behaviors depends on random variables. Per execution of rule (4), (5), and (6), a random number from 0 to 1 is sampled before positioning an agent. "Most" signifies that an agent will act if the random number is within the interquartile range (IQR, middle 50%). Within this VPL interface, the behavior rules are integrated with geometry optimization. During BPS, all the information gained from the ABM is fed into a form optimization process. This experiment employed adaptive pattern-search hybridized simulated annealing (T-APSSA), which can locate a global optimum in a discrete search space within a smaller number of iterations compared to SA or generic algorithm (GA) [37]. The pseudocode (Figure 5) shows how optimization geometry is obtained in conjunction with the simulation of the ABM-based human–building interaction.

```
Pseudo code for ABM-based geometry optimization
algorithm dynamic behavior-geometry ABM is
    input: Building geometry G(p) with the number of windows and doors n_w and n_d,
           number of agents in each group (A, B, C), a_n, b_n, c_n
           Initial heating and cooling set point temperature, t_h, t_c
    output: Geometry G(p)* such that total energy use (E*) is minimized

    while t > t_min
        generate a series of the geometry parameter p_1, p_2, p_3, … p_m, … (m ≤ 8)
        get a random solution G(p) and E
        for each p
            initialize agents in space
            write G(p_m) in .idf format
            initialize BCVTB and EP (import a weather file)
            set SA initial and terminating temperature, t, t_min, and cooling rate α (0 < α <1)
            e_m (energy use of G(p_m) at this time) := 0, E_m:= 0
                for each time step
                    run EP and get e (current energy use), T_room, t_h and t_c
                    for each agent, A_u, B_v, C_w
                        calculate T_skin, check ABM rules and allocate A_u, B_v, C_w
                    set new t_h and t_c
                    display T_room and e in GH
                    e_m += e_m
                end
            E_m:= e_m
        G_new(p) = min_E[G(p_1), G(p_2), …, G(p_m), … ] and get E_new from G_new(p)
        if E_new met a convergence condition, then terminate the loop and G(p)*:= G_new(p)
        else if E_new < E or exp((E – E_new)/t) > random(0,1), then G(p)*:= G_new(p) and E* = E_new
        t = tα
    end
        return G(p)*
```

Figure 5. Pseudocode of ABM-based building form optimization.

Moreover, for the second RA layer, we assumed that every agent has its own thermosensitivity. Each individual is likely to have a different optimal level of thermal comfort. To explore how agents' thermal senses influence space temperature change and energy use, we added the following thermal control scenarios (S.1~S.3).

(S.1) Air-conditioning systems operate from 8 a.m. to 6 p.m. During operation, building users have full access to thermostat control. The systems are designed to have dual set points for heating and cooling.

(S.2) Group A is sensitive to slight over-heating. If their skin temperature increases above 33°C, and the ratio of the number of Group A agents to total occupants is greater than 0.5, the agents will change the set point temperature of the cooling equipment to 28°C.

(S.3) Group C is sensitive to over-cooling. If their skin temperature drops below 32°C, the cooling equipment will be turned off.

These scenarios were tested in a hot local climate (Miami, USA) using an electric heat pump with 14 seasonal energy efficiency ratios (system sizing was automatically set by EP). Agent action along with the random fenestration design of a room shape produced different thermal environments. The adaptive space thermal environment was monitored every 15 min, which is the time step subject to the resolution of EP simulation. Realistically estimating personal thermal sensation involves a highly complex physical relationship between various factors such as air velocity, humidity, and radiation, among others [38]. As a design game, this experiment set a limit on complexity, focusing more intensely on the relationship between room geometry and occupant behavior. Skin temperature (T_{skin}) was estimated as an average temperature of local body parts and represented by personal clothing insulation level (*clo*) and zone mean air temperature (T_{room}), such that T_{skin} = [{(0.155*clo* + 0.115)T_{room} + 3.795}/(0.155*clo* + 0.23)] [39]. To render this formulation as a stochastic characteristic of each agent, clothing level was represented approximately with probabilistic distribution (normal), setting other simulation parameters to constant values (Table 1).

Table 1. Behavior-related BPS input factors [6,40].

Clothing Insulation Level (*clo*)			
		μ	σ
Summer: day		0.32	0.08
Summer: night		0.15	0.05
Winter: day		0.9	0.09
Winter: night		1.38	0.11
Auxiliary Parameters			
	Base	***Min.***	***Max.***
Lighting power: general (W/m^2)	13	11	15
Lighting power: intense (W/m^2)	15	11	19
Appliance density (W/m^2)	15	12	22
Occupant metabolic rate (W)	80	70	130

3.4. Agent Positioning Model: Gaussian Process Classifier

In this ABM framework, we assumed that agents are active and intelligent enough to find the best spatial positions for themselves. They are short-memory entities characterized by the Markov property. Individuals remember their specific spatial positions at a present time step and use them to move to the next place. To make decisions about their own movements, agents use a Gaussian process classifier (GPC) to identify positioning suitability based on the information of geometrical room characteristics and other agents' space occupancy.

The Gaussian process (GP) is a machine-learning extension of the multivariate Gaussian in which the probability function values correspond to random output. GP assumes that the output data are jointly normally distributed using a non-parametric Bayesian model. Posterior inference is made without prescribed model parameters but only by random functions drawn from the prior. GP makes sense in cases where it is likely to assume normally distributed data association for inference, especially when predictions must be made with little information about data.

Suppose that we have a dataset D of n observations, $D = \left\{\left(x_p,\ f_p\right)\middle| p = 1, \ldots, n\right\}$, where $\boldsymbol{x}$ is a m-variate input vector, $\boldsymbol{x} \in \mathbb{R}^{n\times m}$ and $f \in \mathbb{R}^n$ denotes a target output from a function $f(\boldsymbol{x})$. Given the training dataset, GP would make a prediction for a new input $\boldsymbol{x}_*$. The joint distribution of the training outputs, $\boldsymbol{f}$, and the test outputs, f_*, is represented using the covariance matrix, K, such that

$$\begin{bmatrix} f \\ f_* \end{bmatrix} \sim N\left(\mathbf{0},\ \begin{bmatrix} K & K_*^T \\ K_* & K_{**} \end{bmatrix}\right) \quad (1)$$

where $y = f(\boldsymbol{x})$ and $y_* = f(\boldsymbol{x}_*)$, and $K = K(X,X),\ K_* = K(X_*,X),\ K_{**} = K(X_*,X_*)$. For $\boldsymbol{x}$, the three types of covariance matrices are defined by

$$K = \begin{bmatrix} k(\boldsymbol{x}_1,\boldsymbol{x}_1) & \cdots & k(\boldsymbol{x}_1,\boldsymbol{x}_n) \\ \vdots & \ddots & \vdots \\ k(\boldsymbol{x}_n,\boldsymbol{x}_1) & \cdots & k(\boldsymbol{x}_n,\boldsymbol{x}_n) \end{bmatrix}$$
$$K_* = \begin{bmatrix} k(\boldsymbol{x}_*,\boldsymbol{x}_1) & \ldots & k(\boldsymbol{x}_*,\boldsymbol{x}_n) \end{bmatrix},\ K_{**} = k(\boldsymbol{x}_*,\boldsymbol{x}_*) \quad (2)$$

where k is the covariance or kernel function used to evaluate the similarity between data points. The kernel is the core ingredient of GP and what makes it different from the general multivariate normal distribution. Rather than relying on a linear product of the deviations of input pairs x and x_*, GP calculates joint probability or covariance by mapping it into implicit feature space using kernel functions. One of the most frequently used GP kernels is the squared exponential, also known as the radial-basis function (RBF),

$$k(\boldsymbol{x}, \boldsymbol{x}_*) = \sigma_f^2 \exp\left(\frac{-\boldsymbol{x} - \boldsymbol{x}_*{}^2}{2l^2}\right) \tag{3}$$

where $\boldsymbol{x} - \boldsymbol{x}_*{}^2$ is the squared Euclidian distance between the two feature (input) vectors, l is the length scale, and σ_f is the variance of the output $\boldsymbol{f}$. In the kernel, σ_f is a scale factor by which the covariance is limited to σ_f^2 at maximum. For multivariate input, a kernel value between two vector points can be obtained by

$$k(\boldsymbol{x}_u, \boldsymbol{x}_v) = \frac{1}{m}\sum_{i=1}^{m}\sum_{j=1}^{m} k\left(x_{ui}, x_{vj}\right), \;\; \forall u,\; v\; \in \{1, \ldots, n\} \tag{4}$$

From (1) and (2), the conditional probability of y_* given $\boldsymbol{y}$ is expressed as

$$y_*\middle|\boldsymbol{y} \sim N\left(\; K_* K^{-1}\boldsymbol{y}, \quad K_{**} - K_* K^{-1} K_*^T \;\right) \tag{5}$$

with $\overline{y_*} = K_* K^{-1}\boldsymbol{y}$ and $var(y_*) = K_{**} - K_* K^{-1} K_*^T$.

Based on the above GP regression scheme, a Gaussian process classifier (GPC) can be obtained by mapping f_* on a sigmoid function, π, such as the logistic function; i.e., $\pi_* = \pi(f_*) = \Phi(y_*)$. An expected mean value of the probability of class membership $\overline{\pi_*}$ is expressed as

$$\overline{\pi_*} = \int \pi(f_*) p\left(f_* \middle| \boldsymbol{f}\right) df_* = \Phi\left(\frac{\overline{y}_*}{\sqrt{1 + var(y_*)}}\right) \tag{6}$$

The GPC provides a prediction to describe building occupant behavior probabilistically with little prior information. The GPC is also efficient at predicting continuous time-series data of unknown occupant activities. For supervised GP modeling, building room designs with different types of space occupancy were generated to create a dataset. As Figure 6 shows, seven features representing space geometry and distances between groups ($\boldsymbol{x_{p1}} \sim \boldsymbol{x_{p\,7}}$) were scaled to [0,1] and matched with binary classification labels (0: not occupiable, 1: occupiable).

On top of this, a simple space transition rule can then be applied. It is assumed that each agent decides whether to stay or to leave at any one time step. Then, we have a state space Ω with two labels such that Ω = {1: stay in the room, 2: leave the room}. Introducing the probability of a transition pair based on a hypothesis, a matrix for occupancy determination (**A**) can be prepared such that **A** = (a_{ij}) = [0.75, 0.25; 0.5, 0.5], where a_{ij} is the probability of an agent to be in state i after being in state j. Combining above rules and model parameters, this eventually characterizes a sort of simple "model-based reflex agent" [17]. According to spatial and environmental information, agents' perceptual activities to maintain specific occupancy states are driven by the GPC model. Unobserved aspects of occupancy are reflected with the establishment of the AI model. The whole ABM scheme is illustrated in Figure 7.

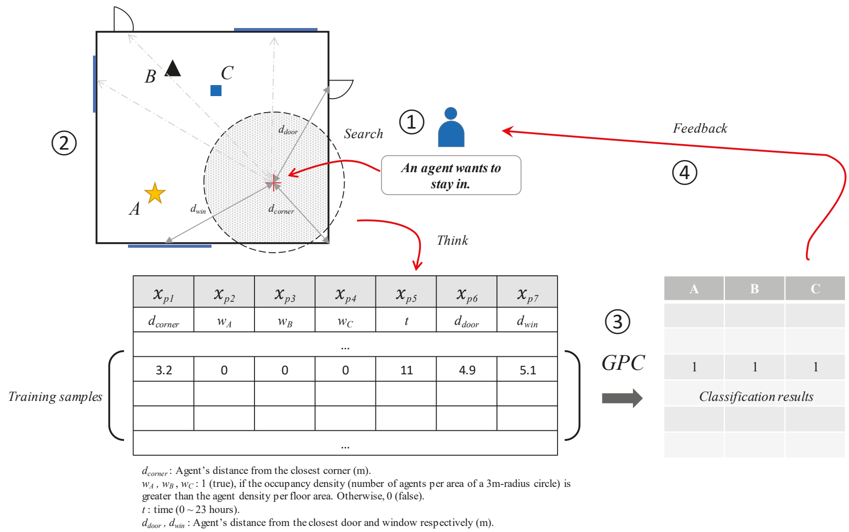


Figure 6. Agents' behavior rule of room occupancy and data format for GP.

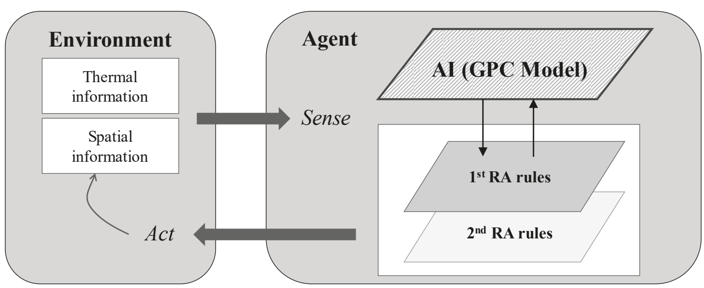


Figure 7. Developed ABM scheme: simple model-based agents.

4. Test Simulation Results and Discussion

4.1. Gaussian Process Prediction Results

The GPC was integrated within the VUI through a Python editor, using the Python machine learning library, scikit-learn™ 0.20.3. A GPC GH module is triggered every simulation hour through BCTVB. To develop the GPC, a training dataset based on the agent rule was created and tested with a simple random building plan. Figure 8 presents the trained GPC's test results and the status of agents' space recognition visually mapped over the building plan. Figure 8a represents a situation with a single agent of each group in the space, while Figure 8b shows a crowded situation with the agents. These results reveal that the ABM behavior rule was successfully implemented through the GPC model.

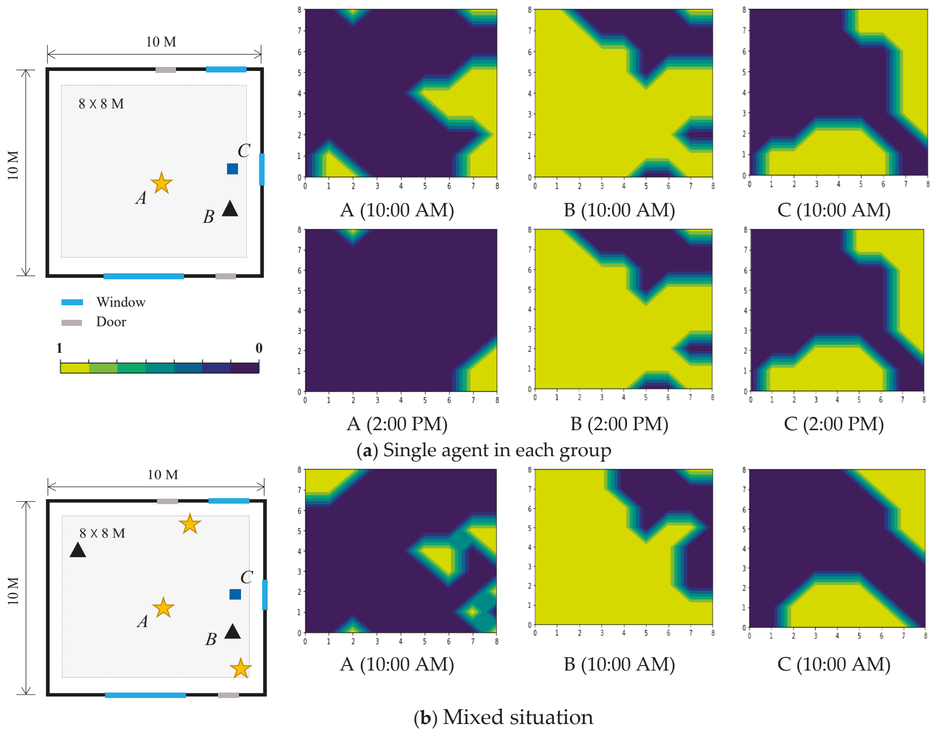


Figure 8. Predicted potential move.

4.2. *Visualized Model Outcome: Generation of Building Form and Space Occupancy*

In the visualization through GH, the geometry's surface color changes depending on room temperature; meanwhile, agents appear in Rhino in different colors according to their groups (blue: Group A; pink: Group B; green: Group C) for every discrete time step (Figure 9; Figure 10). Once a user draws a planar line/curve to design a space, a 3D building model with random window/door designs is generated and the ABM simulation is executed. During simulation and optimization, agent movement and geometry changes occur simultaneously, maintaining design constraints and ABM rules. At the initial stage, human figures are randomly spread out over the building floor within a space outline, and their positions are recorded in the ABM memory.

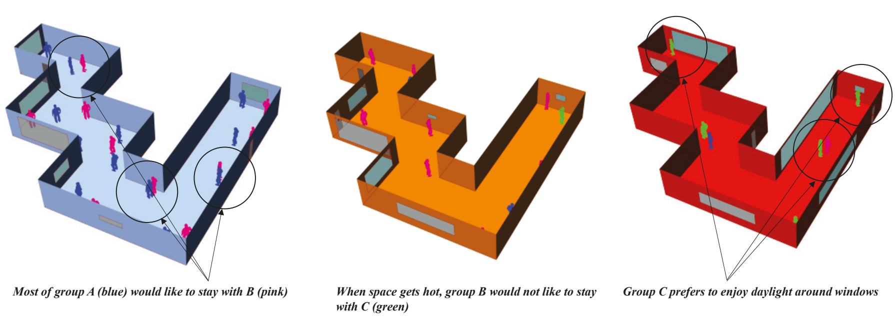


Figure 9. Change in room occupancy according to agent rules.

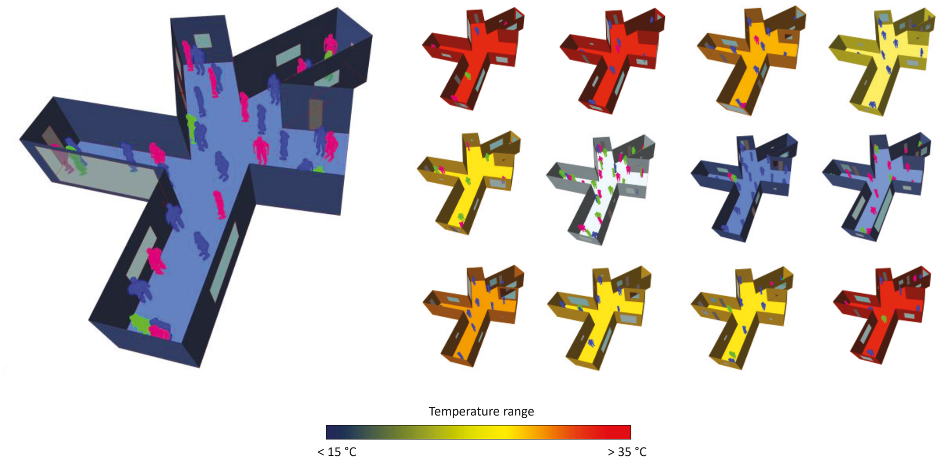
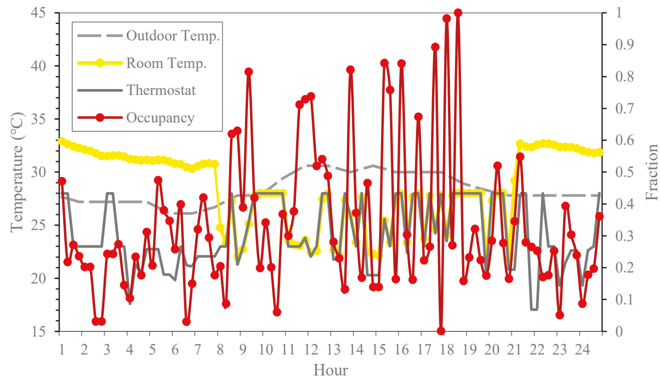


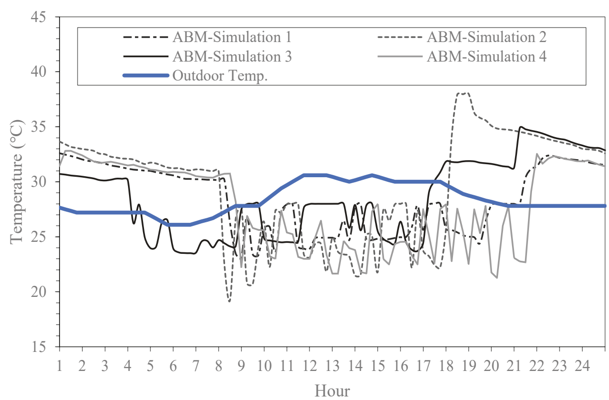
Figure 10. Visualized adaptive geometry in automated optimization process.

4.3. Analysis of BPS Results

The results of EP simulation (space (room) temperature and energy use) are displayed on a graph dashboard in the VPL interface (Figure 2) to enable the user to monitor the dynamic ABM simulation process. As a pilot test, ABM was simulated with the geometry shown in Figure 10. Like any public space, this space has no specific function, and the agent rules only govern how to use the space. The total floor area is 750.58 m^2, and the number of agents in each group was set to 25 so that the maximum occupancy load would not exceed 10 m^2 per person, which is the limit for a typical office. To test a space's adaptability under extreme conditions, the simulation period was set to 24 h during the day of summer solstice (21 June). Figure 11; Figure 12 present the test results. Figure 11a shows large fluctuations of space occupancy due to the GPC and the agents' stochastic transition rule. The average outdoor temperature in the morning and during the nighttime was around 27.6 °C, while the unconditioned room temperature reached 4–5 °C higher than this. During system operation (*S.1*), it was possible to identify variations in the thermostat set points according to agent rules (*R.1~6*) and scenarios. As a thermostat setting changes, room temperature dynamically changes at each time step. ABM does not provide a single solution—instead, due to its randomness, there are as many solutions as the number of simulation runs. Figure 11b plots four different results of ABM simulation. In Figure 12, compared to constant thermostat control (non-ABM), ABM demonstrates that active occupant engagement can ensure energy-saving potential with flexible system operation. While the simulation result only considering variable occupancy (gray line in Figure 12) does not show a major difference, the end energy use of ABM simulation noticeably increased from 0.24 GJ (0.32 MJ/m^2) to 0.32 GJ (0.43 MJ/m^2). Although the occupant-driven operation did not lead to energy reduction in this case, this result indicates that energy-conscious behavior would benefit building energy use. Moreover, the suggested interface will be helpful in testing dynamic energy performance in advance at any stage during design.



(**a**)



(**b**)

Figure 11. ABM simulation results: (**a**) space occupancy and temperature; (**b**) temperature variations of different simulation runs.

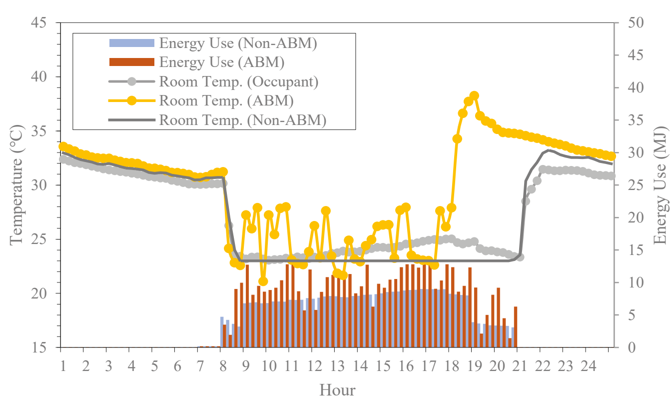


Figure 12. Comparison of ABM and non-ABM simulation.

5. Concluding Remarks

Currently, advanced simulation techniques regarding human behavior call for a transformative approach to sustainable building design methodology. This is because conventional approaches to sustainable building design primarily emphasize time-tested evidence and in-depth engineering pursuits that are invisible to architects. Although early design phases must be sufficiently informed by real-world parameters and design concerns, the existing tools and methods are not fully supportive for architectural practice.

An important way to make PBD more accurate is to couple the process of single-purpose simulation with real-world parameters to strengthen the responsive (feedback) mechanism between a digital environment and actual representation. Adding "real" properties to BPS will not only greatly improve the reliability of simulation outcomes but also help users to envision new possibilities of BPS application to environmental architectural design—for example, real-time accessibility and prediction of building conditions and behavior, building operation resilience, or preemptive building diagnosis.

In order to propose a more interactive and dynamic PBD process, this study suggested a design-oriented multi-dimensional PBD system using digital building modeling coupled with artificial behavior imitation and simulated data analytics. To this end, the study has pioneered the dynamic integration of ABM and BPS through the parametric interfacing of an automated design process using GH as a VPL, demonstrating that coupling PBD with human behavior can serve as a novel architectural design process. The study's results showed that this ABM framework can significantly make design more intelligent and strengthen the power of simulated worlds beyond mere technical merits. The ABM-based, decision-support interface proposed herein can help designers easily access building thermal information and quickly explore various design options through seamless automation. Moreover, the visualized thermal environment and occupant behavior in a given space can focus our attention on feedback loops between a built form and usage patterns as well as the importance of human-building interactive design to achieve sustainability.

The study's proposed ABM is based on building users' realistic attributes, but the behavior rules employed here were hypothetical. Thus, the different agent scenarios must be validated through comparison with actual social human interaction. To improve data quality and outcome precision, an in-depth analysis of actual building use patterns is necessary. Further studies might employ questionnaire surveys or monitoring of human activities to develop a more robust agent model. Tether-free data communication, sensing of physical systems, remote visualization, and self-adjustment in data transmission related to cyber-physical system (CPS) integration can also be taken into consideration in future research.

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sustainability

Article

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

Seung Wan Hong [1], Hwanjin Kim [1], Yongjun Song [1], Sung Hoon Yoon [2] and Jaewook Lee [3,*]

1 Department of Architecture, Inha University, Incheon 22212, Korea; hongsw@inha.ac.kr (S.W.H.); 22201143@inha.edu (H.K.); 12151029@inha.edu (Y.S.)
2 Department of Architecture, Cheongju University, Cheongju 28503, Korea; shyoon@cju.ac.kr
3 Department of Architectural Engineering, Sejong University, Seoul 05006, Korea
* Correspondence: jaewook@sejong.ac.kr

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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).

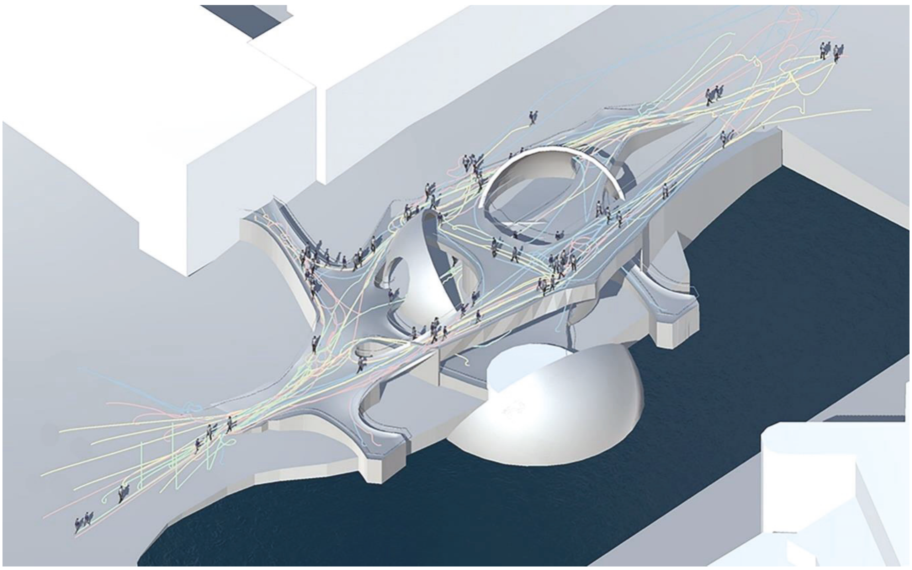


Figure 1. An example of a human behavior simulation. In a community center project, students analyzed accessibility and interpersonal interactions through the use of human behavior simulation [25].

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.*

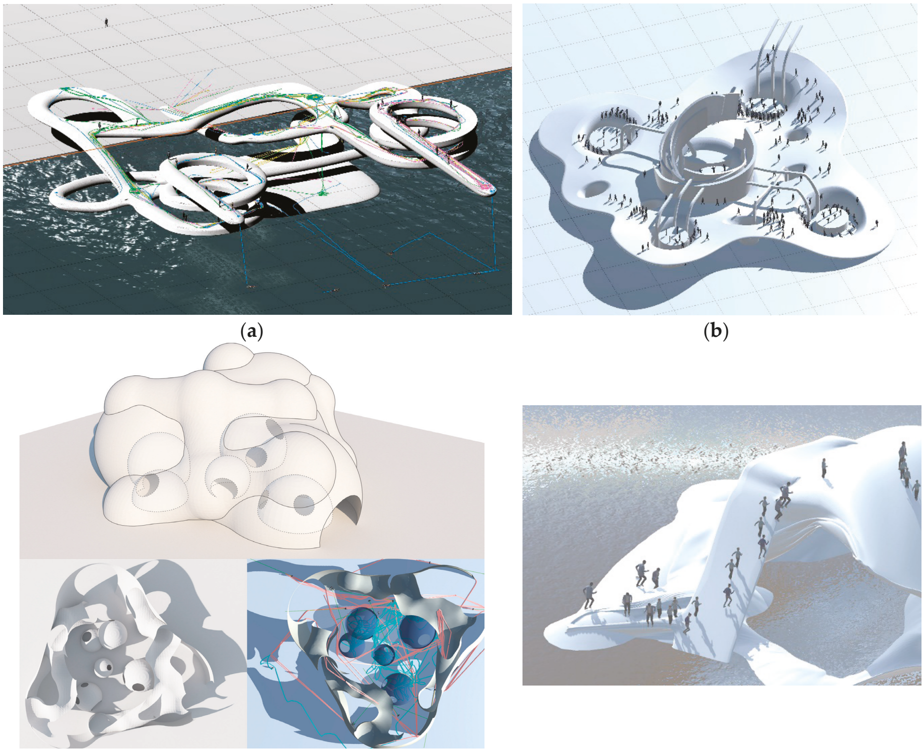
Hypothesis 4 (H4). *In students' experimentation and learning outcomes, human behavior simulation better improves the physical attractiveness of the built environment than its absence does.*

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.

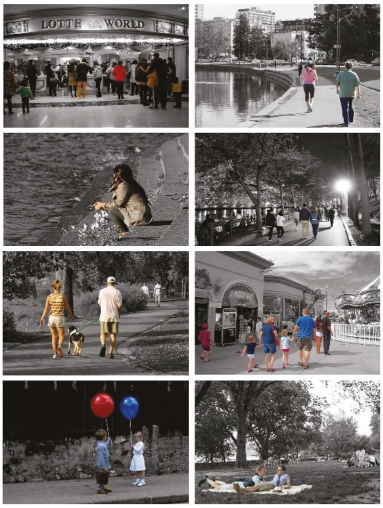


(**a**) (**b**) (**c**) (**d**)

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.

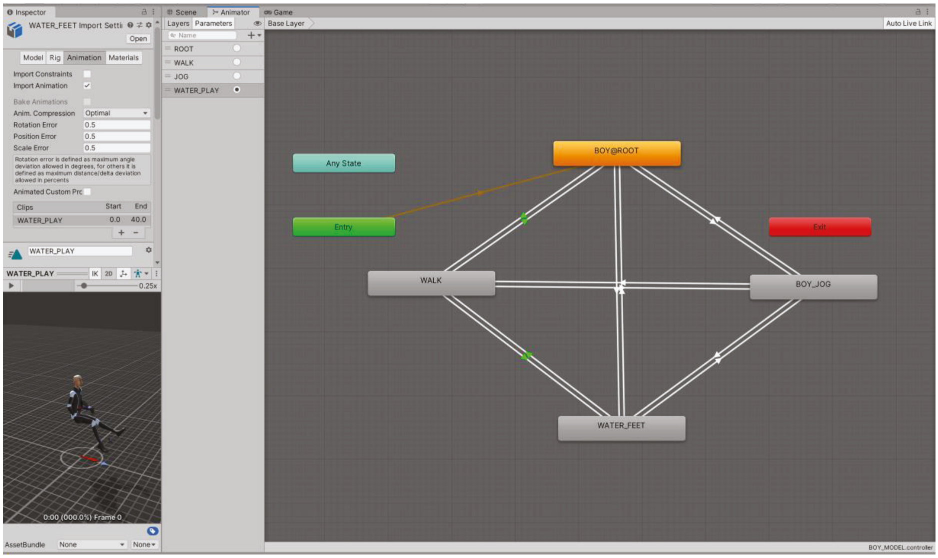


Figure 4. An example of the finite-state machine in Unity 3D [33].

```
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;
}
```

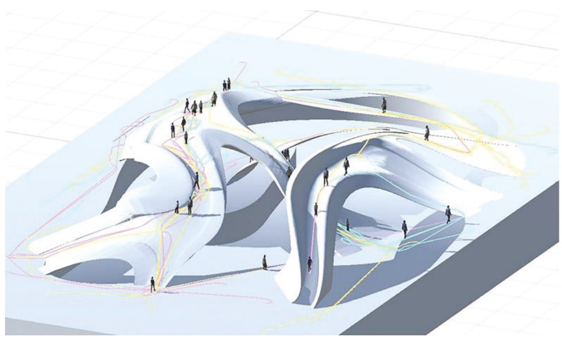
Figure 5. An example of behavior transition codes in C# [33].

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).

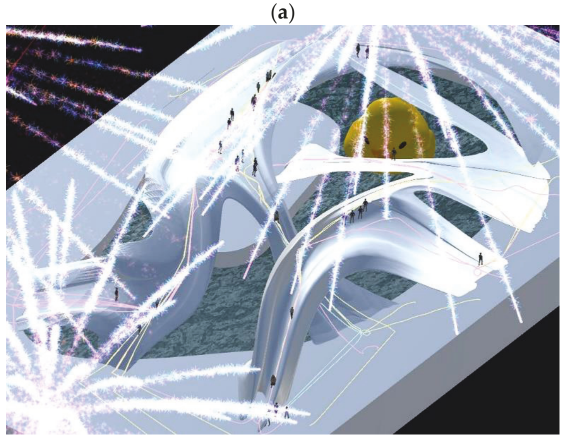
```
void Update()
{
    if (preferFirework == true)
    {
        Watch_Firework();
    }
    else if (preferDuck == true)
    {
        Watch_Duck();
    }
    else if (preferFirework == false || preferDuck == false)
    {
        if (preferWater == true && seeWater == true)
        {
            if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

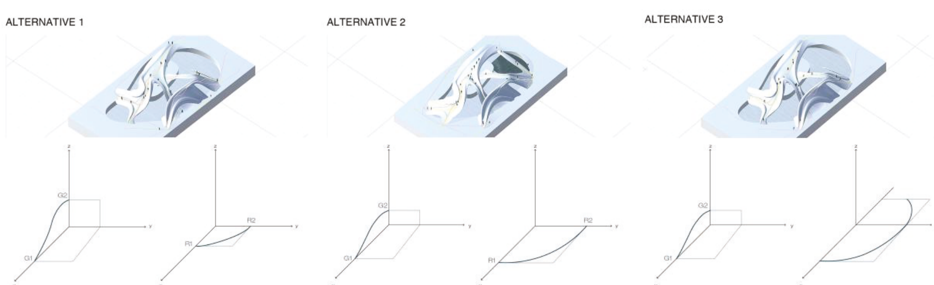


(**b**)

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).



ALTERNATIVE 1

	gradient G (°)	radius R (m)
Area A	60°	–
Area B	25°	2.5m

ALTERNATIVE 2

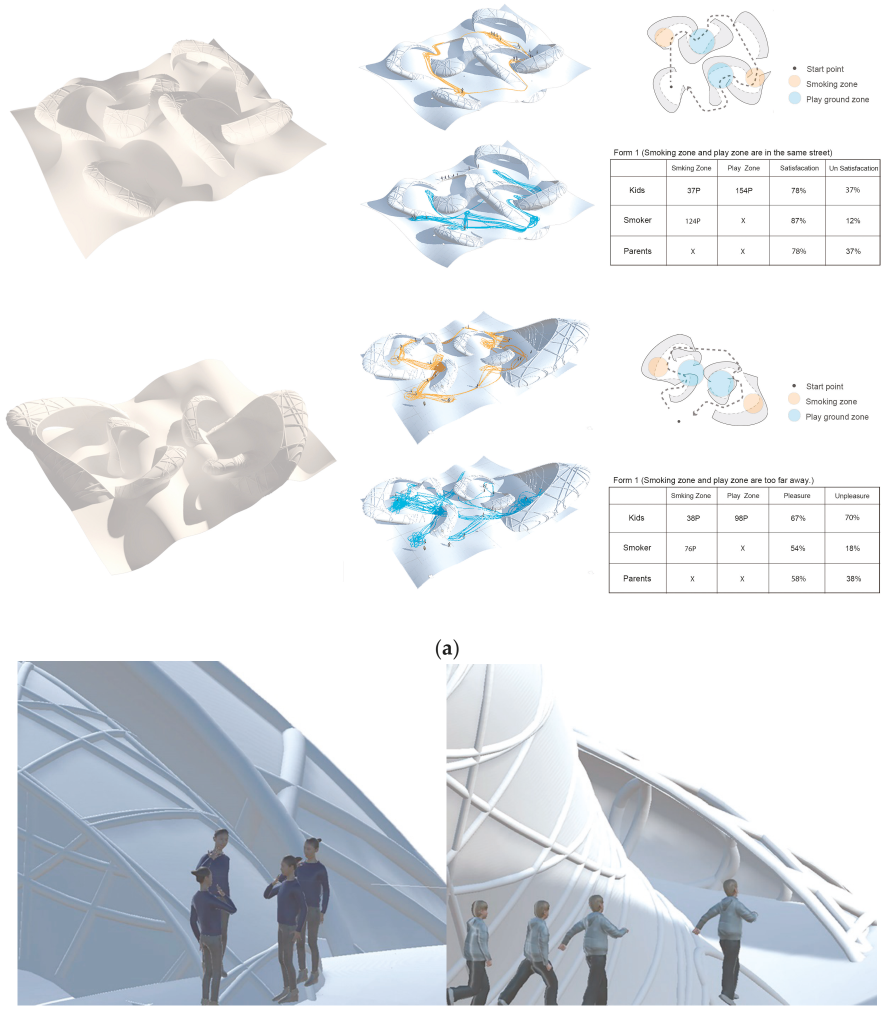
	gradient G (°)	radius R (m)
Area A	45°	–
Area B	25°	5m

ALTERNATIVE 3

	gradient G (°)	radius R (m)
Area A	45°	–
Area B	20°	8m

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.



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

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

(**a**)

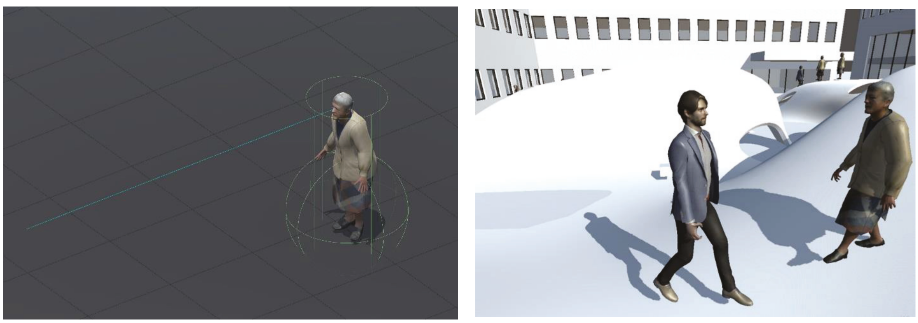
(**b**)

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).

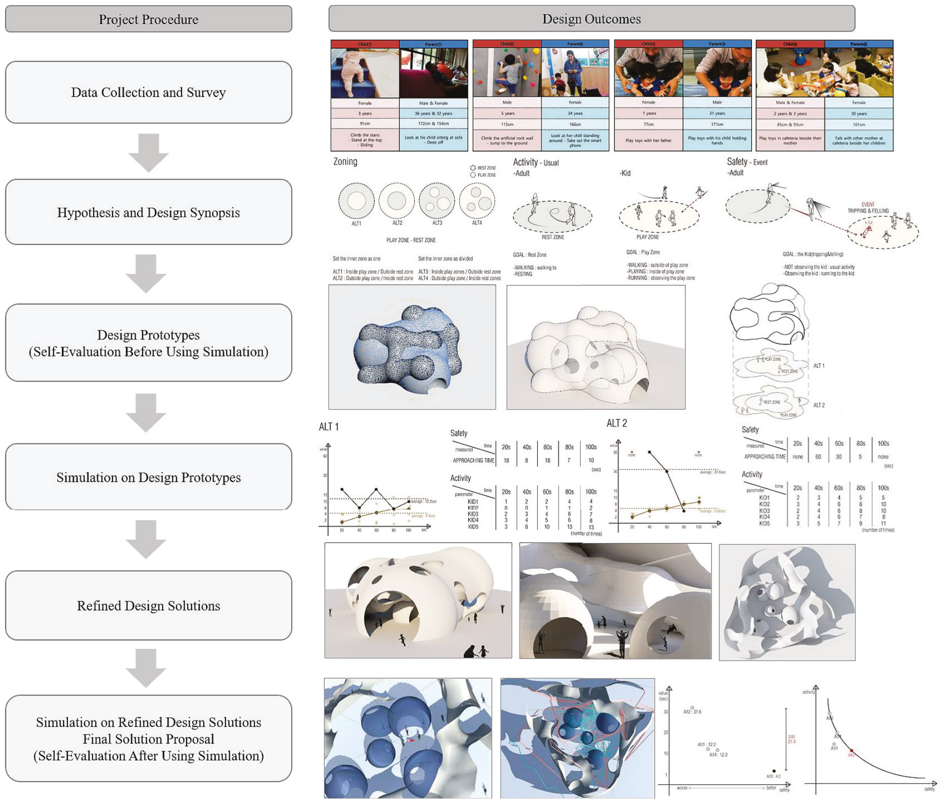


Figure 11. Project procedure and samples of design outcomes [31].

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.

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Article

Using Eye-Tracking Technology to Measure Environmental Factors Affecting Street Robbery Decision-Making in Virtual Environments

Jae weon Yang [1], Dowoo Kim [2] and Sungwon Jung [1,*]

[1] Department of Architecture, Sejong University, 209, Seoul 05006, Korea; zzmessyzz@naver.com
[2] Department of Police Science, Kyungnam University, Gyeongsangnam-do 51767, Korea; whitecrow@nate.com
* Correspondence: swjung@sejong.ac.kr; Tel.: +82-2-3408-3289

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Abstract: There is a lack of quantitative data regarding how offenders make decisions about committing a crime or how situational factors influence such decisions. Detailed crime data on decision-making among criminals are required to improve the accuracy of research. Demonstrating a new methodology for assessing the factors impacting criminal decision-making among street robbery offenders, this study identifies visual data that influence criminal decision-making, and verifies the significance of the measured data. To this end, this study first identified and organized the physical aspects affecting criminal decision-making based on the Crime Prevention Through Environmental Design (CPTED) literature. Next, participants were informed of a street crime scenario and asked to replicate the behaviors of criminals in the virtual environment of Grand Theft Auto 5. Factors affecting criminals' decision-making were then quantitatively assessed using eye-tracking technology. Multivariate logistic regression analysis was used to verify the significance of the measured data. Results show that windows placed adjacent to the street, balconies and verandas, and signs indicating territoriality have a significant effect on criminals' decision-making. Confirming the influence of CPTED factors on the occurrence of street robbery, this study advances a new way of acquiring quantitative data through eye-tracker technology, a method hitherto unexplored by existing research on street robbery.

Keywords: eye tracking; virtual environment; street robbery; CPTED; crime prevention; fixation count

1. Introduction

1.1. Background and Purpose of the Study

The occurrence of street robbery is influenced by a number of factors, including the criminal's behavior, the victim's vulnerability, appropriateness of the location, and people's daily activities [1]. Street robbery data and existing studies also indicate a high probability of street robbery reoccurring in the same locations [2–5]. Such findings enable the examination of the environmental factors of locations where street robbery frequently occurs [2]. Nonetheless, we were hitherto unable to identify latent street criminals in reality or predict the occurrence of street robbery. There is a growing recognition of the importance of Crime Prevention Through Environmental Design (CPTED), an approach seeking to lower the crime rate by creating environments that hinder its occurrence. Although existing criminal research has focused on criminals' biological and psychological features, scholars are becoming increasingly interested in predicting crime based on situational factors, including CPTED elements that make crime more likely to occur in certain locations [2,6,7]. Situational factors affect the process of criminal decision-making, with related studies conducted on the basis of crime theories and analyses of post-incident crime data [2].

Three types of crime data are used in current criminal research. First, scholars like Armitage [8] have surveyed convicts in order to establish crime data based on the analysis of criminal behavior. This data type is particularly popular. For instance, Weisburd [2] found the surveying of individuals to be the dominant unit of empirical analysis in almost two thirds of the articles published in *Criminology*. However, this method does not allow for the quantitative testing of the impact of different environmental characteristics (as in the CPTED approach) in the offender decision-making process. Consequently, it is difficult to gather precise data from offenders [8]. The second type of data is open crime data. Comprising time and location data, open crime data are frequently used by programs like PredPol and HunchLab to predict crime. Open crime data are recorded by police and related organizations through the reports and testimony of victims, but they are limited insofar as they do not include any other specific details. Nonetheless, these data include a range of data from the macro level (including cities, counties, and states) to the meso level (such as census tracts, census block groups, and neighbors) [2]. The third kind of data consists of micro-level factors regarding the crime location. Related studies are currently limited. According to Weisburd [2], only 4.3% (31) of the 719 papers submitted to *Criminology* over a 25-year period analyzed micro-level factors affecting crime. This may be due to the difficulties associated with conducting micro-level analysis in current criminal research.

As such, a new method of analyzing the environmental factors that form the basis of criminal decision-making is necessary to overcome the limitations inherent in existing research. Quantitative measurements of micro-level factors are also necessary to ensure objective results. Addressing this need, this study proposes the use of eye-tracker technology to measure the time and frequency with which street robbers fix their gaze on surrounding elements that affect their decision-making. Using the virtual environment of Grand Theft Auto 5 (GTA5), a game acclaimed for its close replication of real environments, this study verifies the effectiveness of the proposed methodology by confirming whether the quantitatively measured values of street elements significantly influenced participants' decisions to commit crime. This study also discusses the usability of the results.

Identifying which street elements significantly affect the criminal decision-making process requires analysis from the criminal's perspective, particularly insofar as visually perceived situational factors constitute the basis of this cognitive process [9]. Accordingly, this study uses eye-tracker technology to gather data from the criminal's standpoint. The eye tracker enables researchers to quantitatively estimate when and for how long a participant's gaze is fixed on an object, thereby overcoming the reliability issue of existing crime data.

Although the environment in which an actual crime is committed needs to be replicated in order to use the eye-tracker measurement method, there is a limitation to replicating criminal behavior in reality. To address this obstacle, this study uses a virtual environment to replicate the occurrence of street robbery. In the virtual environment, the eye tracker measured the situational factors that might affect decisions to commit crime.

1.2. Street Robbery and Bounded Rationality

In general, research on criminal behavior can be divided into two fields: situational criminology, which analyzes the situational elements of the site where crime occurs, and criminal psychology, which studies criminal behavior. The situational approach of routine activity theory conceptualizes street robbery as a fundamental criminal behavior [10]. According to routine activity theory, places where street robberies frequently occur have a pattern facilitating the occurrence of crime. Certainly, both criminological theory and actual crime incidents indicate that crime is more likely to happen in certain locations [10]. Based on such theoretical grounds and the empirical evidence provided by crime data analysis, we can derive the locational conditions influencing the criminal decision-making of street robbery offenders. In this respect, extant research indicates that offenders first consider the situation—such as the target's vulnerability and the appropriateness of the location—before committing the crime [11]. In terms of location, street robbery occurs more frequently in densely populated areas [11], particularly urban centers [12]. Street robbers typically select a target location close to their residence as they seek familiar locational conditions [12]. Furthermore, street robbery frequently occurs in garages, public transportation sites, and parking lots in urban centers [13]—that is, environments that promote people carrying cash [12,13].

The majority of studies analyzing criminal behavior under the aforementioned conditions adopt rational choice theory [14], understanding the decision to commit a crime as the outcome of comparing the benefits and risks entailed in doing so [15]. Such research indicates that criminals tend to target distracted individuals who appear to possess abundant cash and valuable goods [16], as well as situations from which they can easily escape and where they can readily monetize stolen goods [2]. However, some critics argue that rational choice theory alone is insufficient for understanding street robbery, particularly insofar as it may not accurately reflect criminal decision-making in real-life situations [17–19]. Scholars have suggested that the criminal behavior of street robbery is more accurately perceived through the "bounded rationality" perspective [18]. Claiming that the process of criminal decision-making is too complicated for the application of rational choice theory in practice, Robles [18] was the first to advance bounded rationality as a perspective that accounts for cognitive and ecological factors as well as rational choice. According to Robles [18], street criminals make decisions based on the simultaneous consideration of situational, social, and environmental factors, and after visually perceiving relevant environmental elements.

As such, although rational choice theory is an appropriate and valuable perspective for street robbery analysis, researchers also need to consider the ecological factors that influence criminal decision-making at the moment of committing the crime. As summarized in Table 1, the extant research indicates that, in addition to the process of rational choice, situational, social, environmental, and temporal aspects are important factors in the criminal decision-making process of street robbers.

Table 1. Factors Affecting Street Robbery.

Category	Factor	Definition
Criminal behavior	Rational choice	Street criminals decide on criminal intent after rationally considering the monetary advantages and disadvantages of committing the crime.
	Ecological factors	The unpredictable behavior and mentality of criminals when committing the crime. Examples include impulsiveness, mistakes, ethical consciousness of criminal behavior, street culture, alcohol consumption, psychoactive substance abuse, collective behavior, and simple behavior [14].
Surrounding situation	Physical factors	Physical factors of the street environment that influence street criminal decision-making (CPTED).
	Social factors	Social characteristics that influence criminal decision-making (e.g., population density, community, and racial diversity).
	Economic factors	Degree to which economic level influences street robbery decision-making. Most street criminals commit crimes for money and other valuables.
	Temporal factors	People's behavioral patterns are affected by routine activities and relate to changes in time. The definition of the behavioral pattern is based on the temporal factors.

1.3. The Need for Smaller-Scale Research on Crime Environments and CPTED Theory

Crime prediction models use open crime data that include basic information such as the type, time, and location of the crime. However, public crime data are limited in scope and do not reflect the characteristics of individuals with criminal records, resulting in the need for studies to control for the variables that significantly impact criminal decision-making. Therefore, further research on more segmented and micro-level factors is necessary to improve the reliability of results [2]. Nonetheless, it is difficult to consider all factor types—that is, ecological, situational, social, environmental, and temporal factors—in a micro-level analysis. Indeed, while most of the factors that affect street robbery decision-making are determined by ecological elements (e.g., impulsiveness, mistakes, the ethical consciousness of criminal behavior, street culture, alcohol consumption, psychoactive substance abuse, collective behavior, and simple behavior), defining a pattern of factors has proven challenging [14]. Moreover, with much of the available crime data based on victim reports, data regarding criminals' ecological aspects are rarely available.

Social, economic, and temporal factors are often represented in statistical data and approached from a sociodemographic perspective. However, despite their high status as quantitative data in criminology research, these factors do not necessarily have a direct influence on criminal decision-making. Consequently, researchers turned to analyzing the physical features of the crime environment as factors influencing criminal behavior, resulting in the development of defensible space theory, CPTED, and crime pattern theory [20], which define the properties of a crime site. For instance, crime rates have been shown to decline as the potential for criminal behavior detection increases [21]. According to these theories, crime rates decrease in environments that facilitate crime detection because fear influences criminals' decision-making in such locations [22].

According to Cozens and Lee [20,22], it is possible to reduce crime rates by reinforcing territoriality, increasing scrutiny of the environment via natural surveillance, and maintaining buildings and streets using the five principles of CPTED. Natural surveillance can occur through buildings adjacent to the street and the absence of obstacles that hinder observation [23]. Cozens [20] argues that natural surveillance via first-floor windows is especially advantageous in terms of spotting criminal behavior. Brown et al. [24] found that balconies and verandas on the exterior of buildings also increase the chance of detecting criminal behavior. Although they hinder intrusion, walls and fences are common obstacles to natural surveillance because they block visibility. Other obstacles include telephone poles, roadside trees, vehicles parked on the street, and front yards [25,26]. Crime prevention grilles placed on windows can also hinder natural surveillance [27,28].

Clearly defined territoriality is also important, with street robbery typically occurring in public places. According to statistical data from the United States [11], the greatest number of crimes occur in non-private, public spaces such as public parking lots, bus stops, and subways. More specifically, street robbery frequently occurs in public parking lots where natural surveillance is hindered by parked cars, providing favorable conditions for escape. Criminals can also hide between parked cars while waiting for victims.

1.4. Use of Virtual Environments

Given that criminals' visual perception greatly influences their decision-making, this study examines criminal behavior by analyzing visual perception in a virtual environment. A virtual environment allows users to freely experience a rendered digital space that appears similar to the actual environment, with user movement monitored through the display [29]. Various industries and research fields have begun using virtual environments and the method of predicting human behavior in virtual reality (VR) has been deemed reliable as the participants are able to freely experience the rendered virtual space and the virtual environment allows for complete immersion [29].

Dibbell [29] was one of the first scholars to examine crime in virtual environment [29]. Extant studies have tended to use virtual environments to examine burglaries—the approach enabling researchers to undertake previously difficult studies that reflect criminal decision-making [29]. In this respect, van Gelder has discussed the extent to which results from criminal research using virtual environments can be applied, and the degree to which psychological and behavioral factors can be realized in virtual environments [29].

This study uses the virtual environment of GTA5, which replicates the urban environment of the Californian city of Los Angeles (LA) in the United States. Developed by Rockstar Games at a cost of over USD 100 million, the game is acclaimed for its close replication of real environments (Figure 1).

According to Filipowicz et al. [30], while not a perfect reproduction of the real world, GTA5 provides a bountiful virtual environment for data collection. Indeed, the game possesses 1000 different artificial intelligence (AI) pedestrians, 262 vehicles, 14 types of weather, as well as realistic bridges, traffic lights, tunnels, and intersections [30]. Offering a first-person perspective of realistic environments, GTA5 negates the financial and technological limitations of creating virtual cities and street environments. Such limitations have impacted the use of virtual environments in street robbery research, which requires the replication of a relatively small space. The virtual environment of GTA5 reproduces street environments accurately enough for the gathering of street environment data for autonomous vehicles, and is even being used to develop autonomous vehicles. According to Davide Bacchet of the start-up car company NIO, virtual environments provide a cost-effective alternative to the limited and cost-prohibitive data available from real roads in developing autonomous navigation technology.

Figure 1. Comparison between the virtual environment of Grand Theft Auto 5 (GTA5) (top) and the real world (bottom).

The creation of visual and auditory environments is essential because street criminals first cognize the threat of detection through sight and hearing during criminal decision-making [18]. Advancing the importance of immersion in studies using virtual environments, van Gelder [31] claims that replicating sound in virtual environments helps enhance users' cognizance of these environments. The sounds in GTA5 increase participants' immersion as they replicate the sounds heard in real urban environments and street robbery encounters, such as screams and police sirens. As GTA5 is run on computers, it was presented to participants on a 21-inch display at a resolution of 1920 × 1080; all lights were switched off to enhance participant immersion. Participants used the game controller Ex-Air to freely explore the virtual Los Angeles environment; this controller was selected due to its popularity, simple controls, and ease of use. Speakers were used to block possible noise from the living environment, thereby promoting immersion in the virtual environment through the cognition of GTA5's soundscape.

1.5. Eye-Tracker Technology

Gaze movement follows the point where an individual's cognition and attention are focused. Gaze fixation and saccade are essential in eye-tracking technology. According to Wedel et al. [32], eye tracking quantitatively outputs gaze, fixation, and saccade, thereby measuring how long an individual's gaze remains focused on a given point [32]. Eye trackers have subsequently been used in psychology and marketing to obtain survey results and have only recently been utilized in community design [33]. Few studies have used eye-tracking technology in the field of community design, and the use of such technology is especially insufficient in research related to crime environments.

Eye-tracker technology includes both fixed and goggle types. A fixed eye tracker can determine where the user's gaze is directed and how long it remains fixed by analyzing the location of their pupils [33]. This study placed a GP3 Gazepoint eye tracker at the bottom of the 21-inch display (Figure 2). A fixed eye tracker was used because the VR of GTA5 is experienced via a monitor and, unlike the goggle type, fixed eye trackers enable participants to become immersed in the experiment without the inconvenience of having to wear the eye-tracker device. Eye-tracker results are presented as quantitative data comprising path and heat map data, which are used to determine the factors cognized by street criminals in the process of criminal decision-making. Participants underwent the process of gaze calibration to increase the accuracy of individual gaze fixation (Figure 3).

Figure 2. GP3 Gazepoint Eye Tracker.

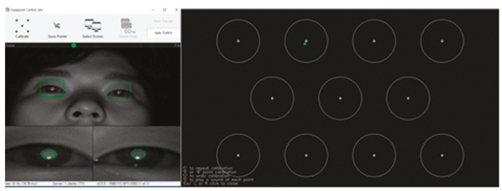


Figure 3. Calibration process of the eye tracker.

2. Methods

2.1. Participants

A total of 20 male university students participated in the experiment. Participants were between the ages of 26 and 29; M (age) = 27.75, SD (age) = 0.967. University students were selected as participants in order to prevent insincere study participation, given that students who are financially dependent on their parents tend to value the participation payment more than office workers. Males were selected because the rate of committing street robbery is considerably higher among males compared to females [1]. Participants' ages, monthly allowances, VR control proficiency, and street robbery experience were surveyed through a questionnaire in the process of setting up the experiment. None of the participants had been involved in a street robbery prior to the experiment.

Participants encountered a scenario in which they were asked to explore the city in search of targets for crime (Figure 4). In the scenarios, participants received preliminary instructions to commit crimes after weighing the risk of detection versus the potential benefits in searching for street robbery targets. The criminal decision-making scenarios were written based on extant research and in a manner that participants could easily understand. Research indicates that street robbers evaluate the suitability of targets based on their visibility, accessibility, and perceived value [34]. Street robbers rationally decide whether the space is familiar and suitable to commit robbery and escape easily [11,12]. The scenarios were provided to help participants consider the process of criminal decision-making for an added sense of reality. Participants were asked to individually search for an environment suitable for committing a crime. To prevent insincere participation, those who committed criminal decision-making without being detected were given an extra reward of KRW 200,000 in addition to the participation payment of

KRW 20,000; those who were detected by the surrounding surveillance environment became ineligible for the participation payment.

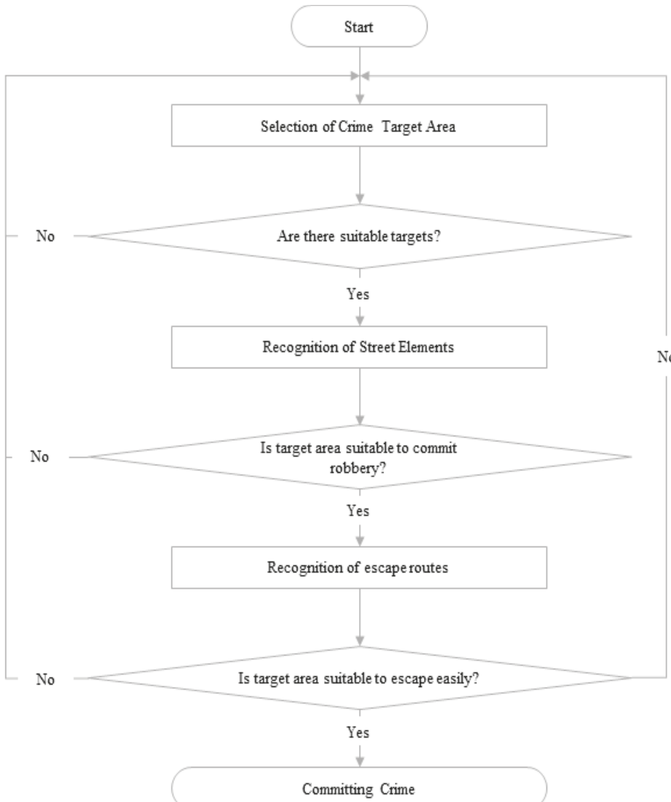


Figure 4. Street robbery scenario.

Control proficiency was evaluated at 1 point for low proficiency and 10 points for high proficiency. To ensure meaningful results, participants were required to achieve five points or higher for control proficiency to proceed with the experiment. This study investigated whether participants' monthly allowance and game control proficiency affected the dependent variable based on the experiment results of the 20 participants.

First, participants' allowances were analyzed due to the possibility of insincere participation by those who receive greater allowances and thus view the experiment compensation as less important. Accordingly, this study investigated the influence of participants' monthly allowance on the results to ensure that the compensation did not influence the research outcomes. Table 2 presents participants' monthly allowances and proficiency results.

Table 2. Participant Statistics.

	N	Min	Max	Mean	S.D.
Age	20	26	29	27.75	0.967
Monthly allowance (KRW 10,000)	20	30	100	58	20.673
VR control proficiency	20	6	10	7.55	1.356

Second, this study investigated the influence of control proficiency to ensure the reliability of the study's results. The extent to which allowance and game control proficiency impact the results was examined through a univariate logistic regression analysis, the results of which are presented in Table 3.

Table 3. Regression Result of Monthly Allowance and Control Proficiency of the Participants in Relation to Criminal Decision-Making Outcome.

	B	S.E.	Wals	Degree of Freedom	*p*-Value	Exp(B)	95% Confidence Interval for Exp(b)	
							Min	Max
Monthly allowance	0.487	0.313	2.417	1	0.120	1.627	0.881	3.005
Constant	−1.298	1.139	1.299	1	0.254	0.273		
Control proficiency	0.447	0.393	1.292	0.1	0.256	1.563	0.723	3.377
Constant	−2.925	2.929	0.998	1	0.318	0.054		

Results yielded significance probabilities greater than 0.05 for monthly amount of allowance spent and game control proficiency, indicating that the variables did not impact criminal decision-making in the virtual environment. Seven of the eight participants who made criminal decisions were successful, indicating sincere participation in the experiment.

2.2. Setting the Scope of Virtual Environment

For the purposes of this study, the experimental scope of the virtual environment in GTA5 consisted of a location replicating a low-rise residential area in LA. The scope was limited to the residential area because street robbers tend to focus on aspects other than the surrounding physical environment in areas that are near a busy street or are commercially active [1]. Moreover, the physical environment has a greater impact on street robbery in residential areas because roads are narrow, and buildings are closer to the sidewalks compared to urban commercial zones. Figures 5 and 6 depict the physical environments of the replicated residential areas used in this study, while Figure 7 presents the experimental scope of the virtual environment in GTA5.

Figure 5. Typical physical elements in an LA residential area: (01) see-through fence; (02) building entrance; (03) first-floor window; (04) surveillance window; (05) balcony; (06) sign indicating territoriality; and (07) parking lot.

Figure 6. Typical physical elements in an LA residential area: (01) see-through fence; (02) building entrance; (03) first-floor window; (04) surveillance window; (05) balcony; (06) sign indicating territoriality; and (07) parking lot.

Figure 7. Scope of virtual environment.

2.3. Setting the Variables

This study considers the role of the surrounding situational elements in the physical environment and rational choice in criminal decision-making. This study controlled for ecological, economic, environmental, social, and temporal factors as follows. First, the ecological aspects of street robbery are difficult to predict. However, as the methodology of this study is bounded to street robbery, which can be defined as a pattern, unpredictable ecological factors are controlled. Second, although statistical data indicate that 95% of street crimes are committed to obtain valuables, it is necessary to consider cases in which the objective of criminal behavior is not money or other valuables when considering the economic environment of a crime [35]. This study controlled for economic elements by selecting university students who are financially dependent on their parents as research subjects. Third, this study defines social factors as population density, social community, and the gap between social classes. This study controls social aspects because it centers on a single research site, and because the participants—who comprise Korean university students from the same social class—cannot be regarded as socially diverse. Finally, temporal factors are also controlled because street robbery occurs at different times depending on people's routine activities [15,36], which means that a set time cannot be defined.

As such, this study examines two variables: rationality in criminal decision-making and the physical environment. Among the physical variables that can be replicated in VR, this study selected factors that affect natural surveillance according to CPTED theory (Figure 8, Table 4).

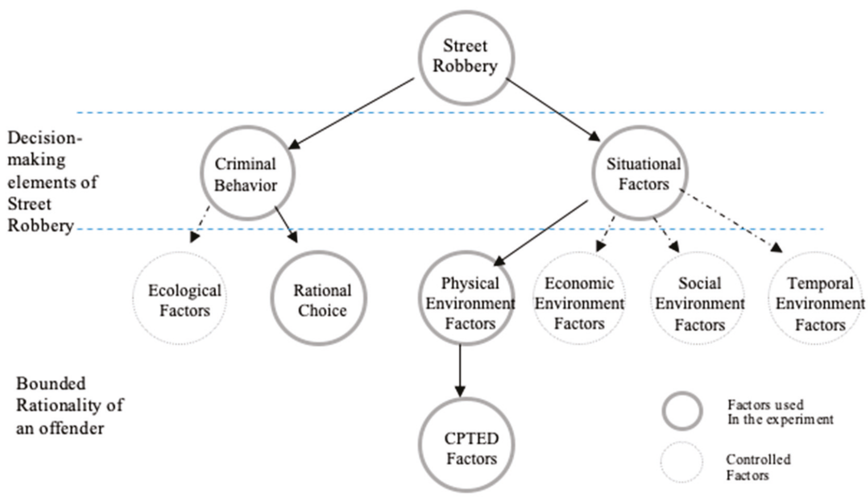


Figure 8. Crime Prevention Through Environmental Design (CPTED) factors.

Table 4. Measured CPTED Factors According to CPTED Theory.

Category	Components in VR	Type
Natural surveillance	NA1. Buildings with entrances exposed to the street (Eye-tracking data on buildings with entrances exposed to the street)	Continuous
	NA2. Exposed balconies or verandas (Eye-tracking data on exposed balconies or verandas)	Continuous
	NA3. Windows exposed to the street (Eye-tracking data on windows visible from the street)	Continuous
	NA4. First-floor windows adjacent to the street (Eye-tracking data on windows adjacent to the street)	Continuous
	NA5. Visibility from main streets (Eye-tracking data on main street traffic)	Continuous
	NA6. Presence of a parking lot (Eye-tracking data on public parking lots)	Continuous

Table 4. *Cont.*

Category	Components in VR	Type
Spatial structure	SS1. Alleys and open spaces (Eye-tracking data on alleys and open spaces)	Continuous
	SS2. Presence of alleys near the crime scene (0 = Escape via the alleyway after committing crime; 1 = Escape through other means after committing crime)	Categorical
Territoriality	TE1. Signs indicating private territory (e.g., signs and murals)	Continuous
	TE2. Territoriality defined by see-through fences (Eye-tracking data on a territory's interior via see-through fences)	Continuous
Maintenance	MA1. Degree of maintenance of the street environment (Eye-tracking data on trash and incivilities)	Continuous

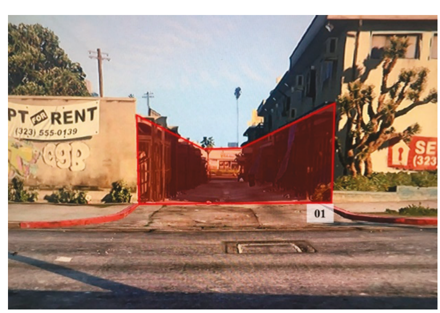
2.4. Measures

Area of Interest (AOI) refers to the object or space on which respondents subconsciously fix their gaze, and it indicates the area in VR to which they pay attention. Two types of data can be assessed through the eye tracker. First, the length of time for which the participant's gaze remains fixed on an AOI is defined as the "time of fixation," reflecting the total amount of time an individual's gaze is fixated on an AOI. Second, the "total number of fixations on AOI" refers to the number of times the participant's gaze is fixed on a single AOI category, indicating the number of times the participant's gaze is directed at an AOI. Figure 9 presents the AOI categories identified in the GTA5 virtual environment.

(**a**)

(**b**)

(**c**)



(**d**)

Figure 9. *Cont.*

(**e**) (**f**)

Figure 9. Area of Interest (AOI) categories in VR; (**a**) 01. Balcony (NA2). 02. First-floor window (NA4). 03. Entrance adjacent to the street (NA1); (**b**) 01. Balcony (NA2). 02. First-floor window (NA4). 03. Entrance adjacent to the street (NA1); (**c**) 01. See-through fence (TE2); (**d**) 01. Alley (SS1); (**e**) 01. Degree of maintenance of the street environment (MA1); (**f**) 01. Parking lot (MA6).

As the time varied for each participant, this study analyzed the data obtained through the eye tracker after dividing the measured data by the time each participant spent on the experiment. The dependent variable is measured as a binary variable, indicating whether a criminal decision was made or abandoned (0 = criminal decision made; 1 = crime abandoned). Detection after a criminal decision is made (detection by police) was calculated as a binary variable for those who made a criminal decision (0 = crime detected; 1 = crime successful). Table 5 presents the variables used in this study.

Table 5. Description of the Variables.

Variable	Description	Type
Time of fixation(s)	Amount of time the participant's gaze remains fixated on an AOI during the experiment.	Scale
Time of fixation/Total experiment time	Ratio of time for fixation divided by the total experiment time; expressed as a ratio due to variation in experiment times.	Scale
Total number of fixations on AOI	Measures the number of times a participant's gaze is fixed on a single AOI.	Scale
Total number of fixations on AOI/Total experiment time	Expressed as a ratio due to variation in experiment times.	Scale
Criminal decision-making	Decision to commit street robbery during the experiment (0 = criminal decision made; 1 = criminal decision not made).	Category
Crime detection	Detection after crime is committed (0 = detected; 1 = not detected).	Category

After beginning the experiment, participants familiarized themselves with the virtual space, perceived their surrounding environment, and searched for potential targets. The physical environment evaluated by participants during the criminal decision-making process was measured using the eye tracker. Figure 10 presents the experimental process from the identification of a target to the making of a decision. Figures 11 and 12 present the examples of virtual environment and gaze fixation. Figure 13 presents examples of gaze heatmaps.

(**a**)

(**b**)

(**c**)

Figure 10. Experimental process: (**a**) Time is measured starting from the moment the participant's gaze fixes on a target; (**b**) the AOI of each physical factor in the street environment is measured; (**c**) criminal decision-making occurs.

Figure 11. Examples of the virtual environment.

Figure 12. Examples of gaze fixation.

Figure 13. Examples of gaze heatmaps.

3. Results

3.1. Eye-Tracking Results

Eye-tracking data on each AOI were produced from the experiment results of the 20 participants, and the importance of the factors considered by participants when actually committing a crime was deduced by analyzing each AOI category (Table 6).

Table 6. Descriptive Statistics of Eye-Tracking Results.

AOI Category	Ratio of Time Spent Time Spent/Total Experiment Time (Ratio A)		Ratio of Fixation Count Fixation Counts/Total Experiment Time (Ratio B)		Avg Ratio A/Avg Ratio B
	Avg	SD	Avg	SD	
NA1	0.055400	0.0139746	0.132920	0.0232209	0.416792
NA2	0.029445	0.0072989	0.067315	0.1378660	0.437421
NA3	0.050575	0.175920	0.133035	0.0474212	0.380163
NA4	0.041840	0.0172831	0.106375	0.0432738	0.393325
NA5	0.058360	0.287291	0.129150	0.0533004	0.451878
NA6	0.014475	0.0075036	0.037320	0.0178688	0.387860
SS1	0.055750	0.0256859	0.129150	0.0533004	0.431669
TE1	0.091315	0.0286507	0.224065	0.0584841	0.407538
TE2	0.073065	0.0188856	0.193940	0.0391037	0.376740
MA1	0.050355	0.221380	0.123190	0.0539619	0.408759

AOI Category Abbreviation

NA1: Building with entrances exposed to the street.
NA2: Exposed balconies or verandas.
NA3: Windows exposed to the street.
NA4: First-floor windows adjacent to the street.
NA5: Visibility from main streets.
NA6: Presence of alleys near the crime scene.
SS1: Alleys and open spaces.
TE1: Signs indicating private territory.
TE2: Territoriality defined by see-through fences.
MA1: Degree of maintenance of the street environment.

Note. Average of total experiment time = 170.8 (s).

As Table 6 shows, the AOI that received the most attention from participants in terms of gaze time and frequency and fixation count was signs of territoriality (TE1), which scored the highest average ratios of gaze time (0.091315) and fixation count (0.224065). As such, participants tended to subconsciously fix their gaze on signs of territoriality longer and more frequently than other AOIs. Conversely, private parking spaces (NA6) yielded the lowest values, with an average gaze time ratio of 0.014475 and average fixation count ratio of 0.037320.

The average ratio of time spent divided by the average ratio of fixation count (Avg ratio A/Avg ratio B) reflects how carefully a participant observed each AOI while gazing at it. Of the possible AOIs, visibility from the main street (NA5) yielded the highest value and was the most carefully observed AOI during the experiment. In contrast, territoriality divided by see-through fences (TE2) yielded the lowest value, with participants quickly shifting their gaze to consider other AOIs.

3.2. Correlation Analysis of Independent Variables

This study analyzed the correlations between the identified AOIs and independent variables. When the p-value is smaller than 0.05 in correlation analysis, the correlation between variables is above 0. Correlation between variables is considerably high when the absolute value of the Pearson coefficient is over 0.7, indicating high multicollinearity in subsequent regression analyses. Table 7 presents the correlation analysis results.

According to the eye-tracking data, building entrances (NA1), exposed balconies and verandas (NA2), and surveillance windows (NA3) exhibit a high Pearson coefficient and p-values below 0.01, indicating that these independent variables have the same effect. Data indicate that potential offenders perceive several elements of a building simultaneously, particularly when windows are situated near entrances and the building has balconies.

Results show a significant correlation between signs of territoriality (TE1) and building entrance (NA1) at 0.992 ($p < 0.01$). This can be explained by the fact that these elements will be cognized simultaneously, with signs and notices displaying territoriality typically installed close to street-side entrances. Results also reveal a high correlation between territoriality defined by see-through fences (TE2) and exposed balconies and verandas (NA2), surveillance windows (NA3), and first-floor windows

(NA4), attributable to the fact that both windows and verandas are included in the region defined by see-through fences.

Table 7. Correlation Analysis Results.

	NA1	NA2	NA3	NA4	NA5	NA6	SS1	TE1	TE2	MA1
NA1	-									
NA2	0.872 **	-								
NA3	0.920 **	0.683 **	-							
NA4	0.576 **	0.381	0.423	-						
NA5	0.865 **	0.773 **	0.889 **	0.144	-					
NA6	−0.137	−0.315	−0.059	0.234	−0.448	-				
SS1	−0.390	−0.586 **	−0.131	−0.588 **	−0.185	0.432	-			
TE1	0.922 **	0.308	0.588 **	−0.312	0.689 **	0.064	0.542 *	-		
TE2	0.461 *	0.749 **	0.900 **	0.699 **	−0.517 *	−0.115	−0.517 *	0.197	-	
MA1	−0.778 **	−0.466 *	−0.831 **	−0.722 **	−0.642 **	0.105	0.387	−0.141	−0.922 **	-

AOI Category Abbreviation

NA1: Building with entrances exposed to the street.	NA6: Presence of alleys near the crime scene.
NA2: Exposed balconies or verandas.	SS1: Alleys and open spaces.
NA3: Windows exposed to the street.	TE1: Signs indicating private territory.
NA4: First-floor windows adjacent to the street.	TE2: Territoriality defined by see-through fences.
NA5: Visibility from main streets.	MA1: Degree of maintenance of the street environment.

Note. * $p < 0.05$, ** $p < 0.01$.

3.3. Logistic Regression Analysis

Regression analysis was conducted to examine the extent to which independent variables affect the dependent variable. As the dependent variable in this study is categorical data, logistic regression analysis is an appropriate means of verifying whether the independent variables have a significant effect on the dependent variable. Logistic regression analysis does not directly predict the occurrence of an event but indicates the probability of the event happening. Accordingly, its value ranges from 0 to 1. A resulting dependent variable value—that is, the probability—greater than 0.5 indicates that the event will occur, while a value lower than 0.5 indicates that the event will not occur.

This study conducted logistic regression analysis to examine the effect of each AOI category on the criminal decision-making process using variables exhibiting high correlations between eye-tracked factors, as identified by the correlation analysis. In this respect, visibility from the main street (NA5) and maintenance of streets (MA1) were excluded from the regression analysis because they showed a high correlation with most natural surveillance factors, which could cause misinterpretation due to multicollinearity. Entrances adjacent to streets (NA1) was also excluded due to a high correlation between this variable and balconies (NA2), windows exposed to streets (NA3), and signs indicating private territoriality (TE1). First-floor windows adjacent to the street (NA4) was analyzed separately as this variable indicated no significant correlations with other variables, and because first-floor windows provide a means of surveillance that differs from that provided by second-floor and side windows, which are not adjacent to the street. Therefore, the independent variables analyzed in this study were limited to NA2, NA3, NA4, NA6, SS1, and TE1.

First, the Hosmer–Lemeshow test was conducted to assess the model's goodness-of-fit using the measured data (Table 8). The Hosmer–Lemeshow test is a goodness-of-fit test deeming a hypothetical model a good fit for the data if the *p*-value is greater than 0.05. If the model passes the goodness-of-fit test, the results of the logistic regression analysis can be considered significant. The test produced a *p*-value of 0.477, which is considerably greater than $\alpha = 0.05$ and confirms goodness-of-fit.

Table 8. Hosmer–Lemeshow Test Results.

	Chi-Square	Degree of Freedom	*p*-Value
Hosmer–Lemeshow test	3.901	3	0.272

Table 9 presents the model's prediction accuracy, with classification accuracy indicating how well the measured data were predicted by comparing the observed and predicted values. A score of 0 (zero) signifies that a criminal decision was made, while a score of 1 signifies that a criminal decision was not made. The model classified the six participants who made criminal decisions and the two participants who abandoned criminal behavior at a 75.0% probability. Conversely, the three participants who abandoned criminal behavior and the nine who made criminal decisions were accurately classified at a rate of 75.0%. Therefore, 75.0% of the 20 participants were accurately classified as individuals who made criminal decisions, as were 75.0% of those who abandoned crime. The results in Table 9 indicate that the model has an accuracy of 75% and is able to predict criminal decision-making at a probability of 75%.

Table 9. Classification of Model Prediction Accuracy.

Observed Value			Prediction		
			Crime Decision		Classification Accuracy %
			0	**1**	
Stage 1	Crime decision	0	6	2	75.0
		1	3	9	75.0
	Total percentage				75.0

Note. The cut-off value is 0.500.

Multivariate logistic regression analysis was conducted to estimate the coefficient (B), its standard error (S.E.), *p*-value, odds ratio (Exp(B)), and the confidence interval for the odds ratio. Table 10 presents the results of the logistic regression analysis.

Table 10. Logistic Regression Results.

	B	S.E.	Wals	Degree of Freedom	*p*-Value	Exp(B)	95% Confidence Interval for EXP(B)	
							Min	**Max**
NA2	0.558	0.268	4.128	1	0.037	1.747	1.033	2.954
NA3	0.525	0.259	4.102	1	0.043	1.691	1.017	2.812
NA4	1.613	0.768	4.408	1	0.036	5.019	1.113	22.627
NA6	0.267	0.211	1.603	1	0.205	1.306	0.864	1.973
SS1	0.266	0.192	1.914	1	0.167	1.305	0.895	1.902
TE1	0.700	0.267	6.857	1	0.009	2.013	1.192	3.400
Constant term	−1.416	0.932	2.304	1	0.129	0.243		

AOI Category Abbreviation

NA1: Building with entrances exposed to the street.	NA6: Presence of alleys near the crime scene.
NA2: Exposed balconies or verandas.	SS1: Alleys and open spaces.
NA3: Windows exposed to the street.	TE1: Signs indicating private territory.
NA4: First-floor windows adjacent to the street.	TE2: Territoriality defined by see-through fences.
NA5: Visibility from main streets.	MA1: Degree of maintenance of the street environment.

Among the variables measured through the eye tracker, variables NA2, NA3, NA4, and TE1 had *p*-values smaller than $\alpha = 0.05$, indicating that each AOI category impacting criminal decision-making is statistically significant. The constant term is not significant because its *p*-value is greater than $\alpha = 0.05$ at 0.129.

The variable NA2, which is the estimated coefficient (0.558) of the time of fixation on balconies and verandas, is the value estimating the change in whether or not to make a criminal decision per ln(P(criminal decision made)/P(criminal decision not made), assuming other covariates to be constant. The variable NA3, which is the estimated coefficient (0.525) of the time of fixation on windows exposed to streets, is the value estimating the change in making a criminal decision compared to not making a criminal decision per ln(P(criminal decision made)/P(criminal decision not made), assuming other covariates to be constant. The variable NA4, which is the estimated coefficient (1.613) of the time of fixation on the first-floor windows adjacent to streets, is the value estimating the change in making a criminal decision compared to not making a criminal decision per ln(P(criminal decision made)/P(criminal decision not made), assuming other covariates to be constant. The variable TE1, which is the estimated coefficient (0.700) of the time of fixation on signs indicating private territoriality, is the value estimating the change in making a criminal decision compared to not making a criminal decision per ln(P(criminal decision made)/P(criminal decision not made), assuming other covariates to be constant.

The odds ratio (1.747) of the variable NA2 is greater than 1, indicating that the odds of not making a criminal decision increase 1.747-fold for every 0.495 s (coding category/average experiment time) spent fixated on balconies and verandas. The odds ratio (1.691) of NA3 is greater than 1, indicating that the odds of not making a criminal decision increase 1.691-fold for every 1.077 s (coding category/average experiment time) spent fixated on windows exposed to streets. The odds ratio (5.019) of NA4 is much greater than 1, indicating that the odds of not making a criminal decision increase 5.019-fold for every 1.196 s (coding category/average experiment time) spent fixated on first-floor windows adjacent to streets. This indicates that windows installed adjacent to streets where crimes occur have a considerable effect on criminal decision-making based on natural surveillance. Finally, the odds ratio (2.019) of TE1 is greater than 1, indicating that the odds of not making a criminal decision increase approximately twofold for every 1.78 s (coding category/average experiment time) spent fixated on signs marking territoriality.

4. Discussion

4.1. Discussion

This study identifies and examines factors influencing criminal decision-making in potential street robbery scenarios in a virtual environment. This study's methodology and results differ from those in extant studies in three ways. First, this study deduces a new type of quantitative data. The quantitative data on physical aspects used in previous research tend to be limited to the number and size of street environment factors, which can be measured within a given space or buffer and have been used together with social, economic, and behavioral factors in large-scale analyses. This study used an eye tracker to assess hitherto unexplored street environment elements influencing the criminal decision-making process. The results of this study can thus be differentiated from those of existing research based on the revealing how the deduced quantitative data directly and significantly impact criminal decision-making.

Second, this study differs from the extant literature in its demonstration of the influence of the physical environment on people's decision-making. Several studies have examined the influence of the physical environment on people and crime using Google Street View. However, this approach is limited insofar as Street View can only be viewed from automobile-accessible streets and cannot provide temporal variables—such as pedestrians and traffic—that influence criminal decision-making [37–39]. In this respect, the use of VR has an advantage insofar as it provides an experience of the physical environment by allowing study participants to freely explore the space.

Third, this study differs from others by using an already developed VR. Previous studies have discussed the use of virtual environments in various ways, with investigations of the psychological factors of criminals made possible by realizing the psychological environment experienced by criminals through VR. As van Gelder [31] notes, the use of VR enables the analysis of criminal behavior by providing an alternative that is able to replicate real environmental factors. Previous studies have used VR to examine burglary, which requires replicating a relatively small space. However, research on street robbery has been limited by the financial and technological difficulties of replicating a city environment. This study overcame such obstacles by replicating a street robbery scenario in the already established VR of GTA5.

The results of this study can be utilized in two ways. First, crime prediction constitutes a significant area of study in contemporary criminal research. For instance, the crime data organized and analyzed by CompStat, a crime statistics system, have been used by programs such as PredPol and HunchLab to predict and reduce crime. CompStat crime data are recorded after the incident based on the reports and testimony of victims. Comprising only basic information such as the location and time of the crime, such data have limited utility for micro-level analysis. Measuring the street environment factors that impact criminal decision-making from a criminal's perspective, the results of this study provide a new type of analytical data on micro-level factors that will enable more accurate crime prediction when used in a crime prediction system.

Second, the findings of this study can be used as reference data when establishing future CPTED evaluation criteria. As the odds of committing a crime fall with the rise in the amount of time a criminal fixates on street environment factors influencing criminal decision-making, it is anticipated that CPTED standards will be established based on the extent to which each factor is exposed on the streets.

4.2. Limitations and Themes For Future Research

Studies utilizing eye-tracker and VR technology face several limitations, with such research being at an elementary stage. The primary objective of studies utilizing VR is to investigate the extent to which criminal behavior and social factors can be replicated through VR, and whether resulting findings are plausible. Such studies essentially analyze the correlation between study results derived from VR and actual crimes. Moreover, in terms of bounded rationality, street robbers' criminal decision-making cannot depend only on the rational choice of the offender. However, this study controlled for the social, economic, and ecological factors influencing criminal decision-making. This issue must be addressed in future research.

The reliability and extent to which participants' cognition of physical factors replicated in a virtual environment relate to reality can be considered a controversial element of this study. This limitation is shared with other studies employing virtual environments; reliability increases in accordance with the similarity of the virtual environment to reality, and the degree to which participants are able to cognize it in a manner similar to reality. In their study using a virtual environment, van Gelder et al. [31] noted that participants lacked sufficient cognizance of the environment due to the absence of virtual entities other than themselves. In the case of GTA5, the existence of virtual entities with individual AIs assisted in replicating a crime scene more closely resembling the actual environment. The presence of virtual entities is especially helpful in replicating the psychological pressure felt by criminals in a crime scenario. VR technology is constantly being developed and becoming increasingly similar to reality. Therefore, the reliability of study results using VR is anticipated to improve in the near future. Moreover, according to Van Sintemaartensdijk et al. [37], when establishing a virtual environment incorporating eye-tracking, researchers need to test the extent to which such elements are clearly visible and whether the gaming experience influences the speed of detection. This should lead to superior automatic recognition by participants, producing more significant results at a behavioral level.

Another limitation of this study involves the design of the research environment: study participants were university students in their twenties and not actual criminals. It is realistically impossible to conduct an experiment with actual criminals as the subjects. While scholars like Garwood (2011), Halsey and White (2008), and Holifreter et al. (2010) advance the potential for university students to commit street robbery, the measurement of their latency is limited. Although this study was conducted on the premise that there is a possibility that the participants could commit a crime, there is a clear difference between the awareness of students and first-time street robbers and that of experienced street criminals, who have a tendency to be bolder and less limited by moral conscience. As such, a research method that controls for these variables is required.

This study is also limited with respect to the number of participants. This study conducted regression analysis with 20 students; however, results would have greater impact if the experiment were conducted with a larger sample. Moreover, the regression model did not consider multi-collinearity.

Consequently, this study only derives possible explanations regarding the relativity between dependent and independent variables. In order to produce more useful regression equations, future studies should be conducted with more participants to yield more accurate results. The correlations among variables must also be considered to produce more significant results.

The degree to which participants can freely control their virtual avatar in a virtual environment may also affect the accuracy of results. While analysis indicated that game proficiency does not impact research results, there is certainly a difference in the cognition of virtual environment between individuals who are skilled at playing video games and those who are not. Immersion is extremely important in virtual environment research (as discussed in previous research), and it is necessary to consider situations where participants may not be able to adequately cognize a virtual space due to differences in individual proficiency with virtual environments.

Future studies should also consider participants' personal behavior and social factors. According to Monk [1], street criminals tend to target those who appear to possess valuable goods, with individual differences in perspective when selecting targets. Moreover, various social variables influence street criminals, such as targeting a specific racial group or selecting vulnerable targets. Social factors merit further consideration for a number of reasons; for instance, the virtual environment used in this study was based on LA, while the participants comprised citizens from the Republic of Korea. Additionally, there may be social and cultural differences among the participants. Although this study was conducted after controlling for factors other than those in the physical environment, this is a problem that must be overcome in future research.

The research scope of this study was a residential area in an urban center in the United States. While street robbery mainly occurs in urban centers, street robbery near the main street is markedly different from that in residential areas and is subject to numerous environmental effects such as the surrounding traffic and presence of commercial areas [12]. In order to explore these micro-level stages, research must be conducted in a virtual environment created through numerous case studies involving analyses of the urban scale moving on to the street scale.

As noted, current crime data consist of fairly simple locational information. If criminal research is to advance, crime data comprising more accurate and micro-level information are necessary. Accurate crime data enable the analysis of criminals' social, cultural, and behavioral factors. Locational data of individual criminal behavior will allow for more comprehensive micro-level crime research by enabling the understanding of future crime environments.

Finally, while a combination of eye-tracking technology and VR allows for the assessment of the speed of crime detection; this feature was unavailable for the current study [33]. Accordingly, future crime research should examine the speed of crime detection using eye-tracking technology integrated with VR, thereby enhancing our understanding of the deterrent effect of guardianship while testing automatic recognition at a behavioral level [36].

4.3. Conclusions

This study demonstrates the use of eye-tracker technology to measure the amount of time and frequency with which street robbers fix their gaze on physical factors influencing criminal decision-making. This study quantitatively measured the physical factors that significantly impact criminal decision-making as a new technique and confirmed its utility in actual crime research by verifying the results through various types of statistical analysis. In doing so, this study contributes to the literature in two ways.

First, this study replicated criminal behavior in VR and identified common street environment factors from those recognized by previous studies using eye-tracker technology. Results show that balconies and verandas adjacent to streets, first-floor windows adjacent to streets, and signs and notices reinforcing territoriality are street environment factors that significantly influence criminal decision-making. While not significantly impactful, other street environment elements affected each participant in a different way.

Second, this study suggested the possibility of predicting street robbery occurrence based on the amount of time participants' gazes were fixed on physical factors significantly impacting criminal decision-making. The longer the time of gaze fixation on street environment factors that significantly affect criminal decision-making, the higher the chance of not making a criminal decision. This finding could become an important standard for determining the physical features that must be exposed to reduce crime when designing buildings in spaces next to streets.

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sustainability

Article

Deep-Learning-Based Stress-Ratio Prediction Model Using Virtual Reality with Electroencephalography Data

Seung Yeul Ji, Se Yeon Kang and Han Jong Jun *

School of Architecture, Hanyang University, Seoul 04763, Korea; musicji83@hanyang.ac.kr (S.Y.J.); seyeon95@hanyang.ac.kr (S.Y.K.)

* Correspondence: hanjong@hanyang.ac.kr

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Abstract: The Reich Chancellery, built by Albert Speer, was designed with an overwhelming ambience to represent the worldview of Hitler. The interior of the Reich Chancellery comprised high-ceiling and low-ceiling spaces. In this study, the change in a person's emotions according to the ceiling height while moving was examined through brain wave experiments to understand the stress index for each building space. The Reich Chancellery was recreated through VR, and brain wave data collected per space were processed through a first and second analysis. In the first analysis, beta wave changes related to the stress index were calculated, and the space with the highest fluctuation was analyzed. In the second analysis, the correlation between 10 different types of brain waves and waveforms was analyzed; deep-learning algorithms were used to verify the accuracy and analyze spaces with a high stress index. Subsequently, a deep-learning platform for calculating such a value was developed. The results showed that the change in stress index scores was the highest when entering from the Mosaic Hall (15 m floor height) to the Führerbunker (3 m floor height), which had the largest floor height difference. Accordingly, a stress-ratio prediction model for selecting a space with a high stress level was established by monitoring the architectural space based on brain wave information in a VR space. In the architectural design process, the ratio can be used to reflect user sensibility in the design and improve the efficiency of the design process.

Keywords: electroencephalography; virtual reality; monument architecture; stress; data visualization; deep learning

1. Introduction

1.1. Research Background and Purpose

According to historians, the chancellor of Germany, Adolf Hitler (1933–1945), had architects create monuments that were a physical embodiment of his worldview and instruments for campaigns against the democratic order. One representative monumental structure [1], the Neue Reichskanzlei, was constructed in 1939 by architect Albert Speer on Hitler's orders [2]. The building was built to showcase the might of Hitler's Germany through its enormity and put pressure on bureaucrats and diplomats based on vertical balance. In 1939, the president of Czechoslovakia attended a political meeting in the Neue Reichskanzlei and passed through its long corridors and high-rise spaces. The spatial dimensions and aesthetics of the chancellery triggered a heart attack in the president. This is one example that shows the overwhelming feeling of the residence [3]. This phenomenon is known as Stendhal syndrome, a phenomenological theory defined by Stendhal in the early 19th century that describes the condition experienced while looking at a work of art at a museum, which includes an increased heart rate, feeling weak in the knees and experiencing ecstasy. This phenomenon has been detected by monitoring brain waves in the medical realm for the purposes of psychological therapy [4].

As such, the residence designed by Speer fulfilled Hitler's grandiose vision (Figure 1). Therefore, in this study, we conducted brain wave experiments to understand the variations in emotions in humans as they move from a low-ceiling space to a high-ceiling space. The emotional information on a person in each situation was analyzed through a fusion of architecture and electroencephalogram (EEG) sensors. We took Hitler's residence as the subject of the case study.

Traditionally in the field of architecture, to infer the spatial experience of a user, which is acquired via a sensor for measuring the physical elements of a building, surveys of the user's reaction and questionnaires are widely conducted. It is possible to develop a method for directly monitoring brain wave information and analyzing emotional information in a space [5].

In this study, we reproduced Hitler's Neue Reichskanzlei or New Reich Chancellery, which is currently in a state of ruin, on a VR platform for a subject to experience. Thereafter, we measured, via EEG signals, the psychological stability index and stress index, which are emotional information indices depicting a subject's feelings in a building space, and built a deep-learning-based stress-ratio prediction model that could be quantitatively evaluated.

1.2. Research Scope and Method

There were two research methods for understanding the stress index for each building space. First, the amount of change in the beta waves of an EEG signal related to the stress index was calculated, and information on the space exhibiting the largest change was expressed in terms of time information from the VR experience. Second, deep learning was used to compute various EEG variables, and batch processing was performed for accuracy improvement. Pattern analysis was performed using deep-learning algorithms to analyze the correlation between ten bits of EEG information and waveforms. During this process, a section with low stability and high stress was identified by considering the correlation between the alpha wave, which indicates psychological stability, and the beta wave, which indicates stress. Thus, the stress ratio was considered in the computation. The stress ratio is defined as the ratio of stress to psychological stability. Subsequently, a deep-learning platform was developed to verify the accuracy and calculate the region with a high stress index. Through a comparative review of the two methods, the region in the VR space where stress was high was identified, and a practical use plan was suggested by monitoring the architectural space of the EEG information.

2. Theoretical Considerations

2.1. Electroencephalogram

An electroencephalogram (EEG) is a measurement of periodic changes in a person's brain nerves, and because it changes according to the state of human consciousness, it is also called "brain potential" or "brain conduction". In general, an EEG is categorized into delta (δ) waves [6], theta (θ) waves [7], alpha (α) waves [8], beta (β) waves [9] and gamma (γ) waves [10].

Furthermore, an EEG amplifies and records the microelectrical activity of the brain via electrodes attached to the scalp with a cap to detect the emotional, cognitive and psychological states that cause certain behaviors [11]. Through this, an unconscious level of cognitive activity can be identified and predicted. In particular, as an objective indicator of brain function and activity level, an EEG is a suitable tool for measuring human sensibility because no other indicators exist that can respond more sensitively to stimulation than an EEG [12].

Previous studies on brain waves have been generally conducted in the medical, biotechnology and architecture fields.

In the medical and biotechnology fields, most studies on the relationship between brain waves and stress have focused on the quantification of stress levels using an EEG to analyze brain waves in the stress state and the rest state for quantification [13]. Furthermore, the stress level was distinguished and quantified using an EEG [14]. Another study analyzed the brain waves affecting stress based on fNIRS (functional near-infrared spectroscopy)–EEG [15]. In addition, one study attempted to improve the accuracy of categorizing stress by converging the EEG and fNIRS measurements [16].

In the architectural field, brain waves are commonly used to measure sensibility according to architectural color; changes according to the variation in architectural environmental elements such as lighting, temperature and humidity; and the responses to changes in visual elements such as specific patterns or shapes.

Studies on measuring sensibility according to spatial color analyzed brain waves by changing the colors of architectural elements such as the floor, ceiling and walls and examined the color arrangements of spaces that are appropriate for relevant space programs [6,17,18]. Studies on measuring the changes in brain waves according to the variation in physical architectural elements such as lighting, temperature and humidity have examined the correlation between environmental changes and spatial satisfaction [19,20]. In addition, studies examining the brain waves' response to changes in visual elements, such as a specific pattern or shape, analyzed emotions by measuring brain waves within specific distances of a city [21,22].

Previous studies investigated the correlation between spatial design elements and brain waves; however, the correlation between stress and brain waves according to the shape or pattern of construction elements for architectural design was not analyzed. References [21,22] are currently conducting studies on specific patterns or shapes; however, there are limitations in analyzing psychological changes according to a specific distance from an urban perspective and applying it to architecture.

Thus, it is necessary to analyze brain waves with respect to architectural elements to increase the efficiency of design and realize a design quality that reflects the user's sensibility during the construction design process.

Accordingly, in the experiment, EEG data were measured, and the change in the stress level according to the characteristics of the space was analyzed when the subject experienced the given space in VR. In particular, there has been an increased need for deep-learning-based technologies for predicting or categorizing definite or meaningful patterns in big data [23] on brain waves, which are collected as 60 Hz or more of unstructured pieces of data per second.

2.2. Virtual Reality

Virtual reality is a technology that simulates an immersive three-dimensional environment or situation similar to or entirely different from reality using a computer. When a dangerous situation or a situation that cannot be experienced in the real world needs to be reproduced, it is possible to build a virtual space in a VR platform and implement a suitable and safe environment to experience it. In architecture, in addition to simulating a computer-generated environment and situation, VR allows users to indirectly experience spaces in a building that will be built in the future [24]. Therefore, VR has been widely used as a tool for practice and research purposes in various fields [25]. One typical example is Unity, which is a VR-capable three-dimensional development platform used to develop interactive three-dimensional content based on the game engine developed by Unity Technologies. It is one of the most widely used tools for game development [26].

2.3. Features of Hitler's Chancellery

The building designed by Albert Speer was based on the concept of "the world in the world". It was designed to control access within Hitler's authority by reflecting his governing philosophy. The chancellery had a sophisticated architecture, giving the impression of a space occupied by a powerful ruler. It was built to show the might of Hitler's Germany and exhibited "greatness" based on vertical balance. Thus, bureaucrats and diplomatic envoys would often express fear when standing in its shadow. An example is the case where Emil Hácha, the president of Czechoslovakia, visited the building in March 1939. The building consisted of plain walls with a 25 m tall floodlight that blocked its space from the outside and four large, smooth pillars arranged around the stairs to add to the overpowering aesthetics of the building. Some theorize that Hácha experienced difficulty breathing as he ascended the staircase that led to the high, narrow entrance through the empty space made by the skylight. Subsequently, he passed the next section of the building, the Mosaic Hall, which was an empty space without furniture or carpets. Weak light bled from the ceiling through translucent glass; however, it was a cold space without shadows and had no purpose other than to have a psychological impact on visitors. The president, who failed to overcome the pressure as he walked through the long corridor after he walked across the rooms, suffered a seizure in Hitler's study and then signed a document known as the Czechoslovakia declaration of submissive surrender [5]. As such, the design of the Neue Reichskanzlei perfectly satisfied Hitler's vision, and it is possible to understand how overwhelming the building was (Figure 1).

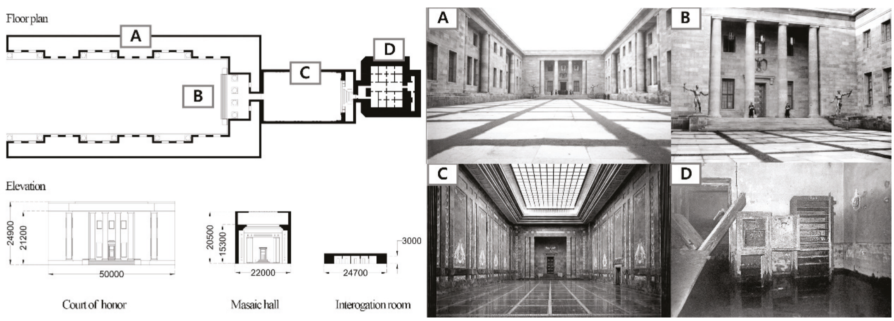

Figure 1. The Neue Reichskanzlei: Adolf Hitler's New Reich Chancellery ((**A**)—Court of honor: Bundesarchiv, Bild 183-E00418/CC-BY-SA 3.0; (**B**)—Court of honor and Mosaic hall transition space: Bundesarchiv, Bild 146-1985-064-29A/CC-BY-SA 3.0; (**C**)—Mosaic hall: Bundesarchiv, Bild 183-K1216-501/CC-BY-SA 3.0; (**D**)—Führerbunker: © Robert Conrad, Bunker Neue Reichskanzlei, Bild 6086).

2.4. Research Contributions

Several experiments are being conducted in the field of architecture to develop and use VR [27] as a method for reconstructing heritage sites because it is not limited by space and time. Based on this method, a space that does not exist or is unsafe for conducting an experiment in can be constructed using VR [28]; thus, the user can indirectly experience a real sense of the space. Furthermore, in recent years, research on the use of the biometric information of users in a VR environment that simulates environments that are otherwise not directly accessible to humans has been gradually increasing [29]. In a previous study, we used a visualization technique employing a VR space. We performed EEG analysis of human experiences according to changes in a residential area consisting of single-person households. We found no significant differences between a human being's emotional response to the actual space and that to the virtual space [25]. In this study, we analyzed the changes in the EEG signals in a VR space and the user's psychological state and attempted to verify the hypothesis that the user's state changes with variations in the floor height of the building through EEG data. This can verify that the psychological state of a human changes with the environment. For example, the huge domelike structure of St. Peter's Basilica and the high ceilings and arrangement of heavy columns of ancient Roman ruins have different impacts on human psychology. These structures often make people feel overwhelmed [30]. Therefore, this study aimed to explain the effect of Hitler's chancellery on visitors by analyzing human psychology through changes in EEG signals with rapid variations in floor height.

3. Experimental Outline and Equipment

3.1. Outline

We reconstructed the Neue Reichskanzlei in a VR platform using historical data. The test subject wore VR gear and EEG measurement equipment and passed through predetermined spaces. The EEG signals were measured, and the stress indices of the subject, which changed depending on the conditions in each situation, were analyzed. VR is not limited by space or time, and any space needed by users can be constructed and experienced. Therefore, in this experiment, the Neue Reichskanzlei, which does not exist anymore (Figure 2, was reproduced and experienced in a virtual space using VR. In the VR experiment, a headset that supports the mixed reality (MR) method was used to indirectly experience the virtual space. As the subject moved and passed through certain virtual spaces during the experiment, the equipment attached to his head measured the EEG signals. Furthermore, because the subject had to wear VR and EEG measurement equipment simultaneously, a piece of equipment with a convenient headband was used to measure the EEG signals.

Figure 2. The demolished Führerbunker in the garden of the razed Reich Chancellery, Berlin (Bundesarchiv, Bild 183-V04744/CC-BY-SA 3.0; Bundesarchiv, Bild 183-M1204-319/CC-BY-SA 3.0).

For the experiment, three spaces of different heights were virtually constructed. The first space was the Court of Honor, with a wall height of 25 m. The second was the Mosaic Hall, with a height of 15 m. The last space was the Führerbunker, with a floor height of 3 m. The subject wore VR and EEG equipment and physically moved in a 130 m straight line to get a more realistic and immersive experience as he moved from the Court of Honor on the high floor to the low bunker in the virtual space. Afterward, the EEG data measured through the experiment were collected based on time-series information. After completing data collection, two analysis methods were employed to determine the stress that the subject felt in a specific space. From the first analysis, a comparative analysis of the types of beta waves, which indicate stress among the spectral information of the EEG signals, was conducted to select the region with the highest stress index. In the second analysis, the stochastic gradient descent (SGD) algorithm and the multivariable linear regression of TensorFlow, which is a deep-learning platform, were used to analyze correlations among the alpha, beta, theta and delta waves to derive regions of stress in order from highest to lowest. The analysis was conducted by considering the correlation between the waveform showing psychological stability, such as an alpha wave, and the stress waveform, such as a beta wave, to find a stress ratio with low stability and high stress (Figure 3).

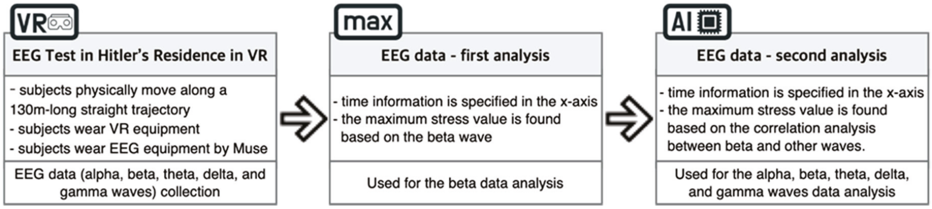

Figure 3. Diagram of the main research process.

3.2. Experimental Equipment

3.2.1. Virtual Reality Instruments

The VR experiment, which was conducted in parallel with the measurement of EEG data, should be conducted in a wide space with a straight line that is long enough that the subject can experience the virtual space while moving directly to a predetermined space at a distance equal to the actual distance. Therefore, the experiment was conducted on a designated long track in the stadium at Kookmin University.

Furthermore, because the method was not at room scale, which requires measurement in a limited space such as the existing VR equipment, an MR method, which can be utilized in an actual space, was used and supported by equipment such as an infrared camera to conduct the experiment. The virtual space for the EEG data measurement and VR experiments was constructed in Unity. The subject wore a Samsung head-mounted display (HMD) Odyssey headset with MR support. HMD refers to equipment that is mounted on the head and completely blocks the user's sight, allowing them to concentrate on the VR simulation. It is also called a face-mounted display [31]. The user may utilize a smartphone, laptop or desktop to run the software, and the visual screen changes as the user moves. With this feature, VR can be input with content that responds to user behavior [32]. Therefore, for this experiment, we had the HMD-wearing user move forward and cross a certain virtual space.

3.2.2. EEG Measurement Tool

Muse [33], an EEG device from InteraXon, was used to measure EEG data. Because the experiment required the user to wear VR equipment and EEG measurement equipment simultaneously, he was given a convenient headband for more comfortable EEG measurements. Because it is dry-type equipment, which is different from conventional equipment that is complex and difficult to attach to a gel- or saline-type device, the device can quickly measure EEG signals and verify data. In a previous study, we used equipment that measured 14 channels. The EEG data yielded few errors due to physical interference between the two pieces of equipment caused by proximity while wearing the headsets. To minimize interference between the EEG device and the VR device and to ensure comfort, a simple device with fewer channels was selected. Muse can collect EEG data from four channels in the frontal (AF7, AF8) and temporal lobes (TP9, TP10) [9]. The locations of channels for EEG data measurement and analysis that were provided by the equipment, such as AF7, AF8, TP9 and TP10, were arranged according to the electrode placement system and typically categorized into the 10–20 international system (IS), 10–10 IS (10%) and 10–5 IS (5%). The number is defined based on the distance between the electrodes and expressed as a percentage, and the 10–20 IS, 10–10 IS and 10–5 IS include the maximum standard positions of 21, 81 and 345, respectively.

Figure 4 compares the electrode locations on the two coordinate systems that are most frequently used in studies and visualizes the locations of the electrodes used in the actual equipment. The electrode location of the Muse equipment for EEG measurement was arranged according to the 10–10 IS and classified according to the part of the cerebrum, left or right, on which the electrode was located [34]. "Frontal polar" is the intersection with the frontal lobe, and "temporal" (T) is the intersection with the temporal lobe. Furthermore, the odd-numbered electrodes were placed on the left side of the head, the even-numbered electrodes on the right side and the lowercase letter *z* indicates the part passing through the center of the head [35]. For EEG measurements, signals were measured at the AF7, AF8, TP9 and TP10 regions of the frontal and temporal lobes by a single-pole induction method based on the earlobe (A1) part of the subject. The measured data were extracted for visualization (Figure 4).

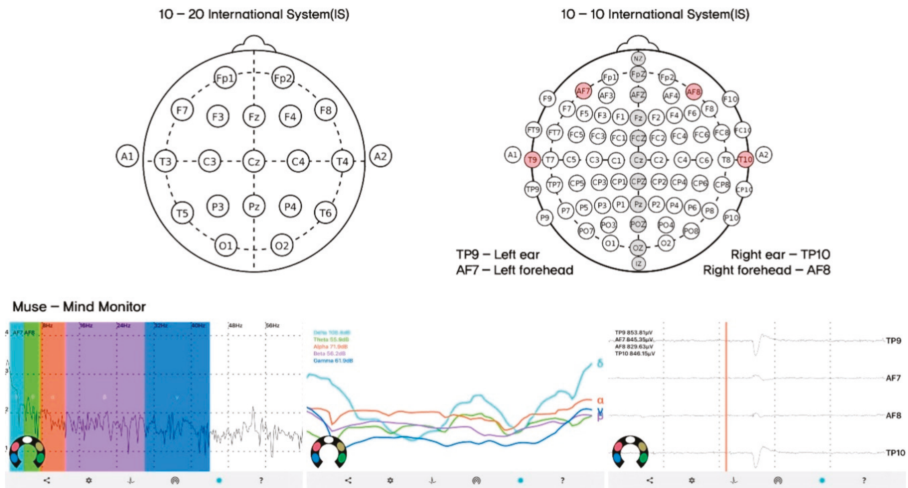

Figure 4. Electroencephalogram (EEG) international system (IS) electrode placement (Muse) and Muse Monitor.

3.3. Experimental Measurement and Methods

3.3.1. Experimental Measurement

The number of subjects for the experimental measurement of brain waves was set to one. We examined changes in brain waves according to the variation in the pattern of building spaces, in which the variables of brain waves were analyzed per frequency using a deep-learning algorithm to find a section with a high level of stress. Therefore, the number of subjects was set to one for the experiment. The subject was a 38-year-old male.

To obtain stable data from the brain wave equipment, a calibration process was required before conducting the experiment. The calibration process, which synchronized the brain wave equipment and the subject, required approximately 30 s. The subject was instructed to clear his mind with his eyes open and remain in a relaxed state for 15 s and then remain in the same state for another 15 s with his eyes closed.

Considering the biorhythm of the subject, the experiment was conducted on 19 April at 12:30 p.m. at the stadium of Kookmin University, in which the subject could walk 120 m of a virtual space in 120 m of an actual space, thus minimizing the discrepancy between the actual space and the VR space.

When the VR program of Hitler's chancellery began, the brain wave equipment started recording data when the monitoring button was pressed. The subject moved through the space in a walkthrough manner from the outside of the building through the inner halls and then into the interrogation room, during which time the process and brain wave data were recorded for analysis.

The subject walked 120 m for 3 min and 47 s. Therefore, the data were collected for 3 min and 47 s, and the sampling rate of the EEG equipment was set to 50 Hz such that 50 pieces of data per second were measured using one piece of data per second using the OSC Stream average option of the Mind Monitor application.

The equipment used in this experiment is described in Figure 5. The EEG data generated from the four channels in the frontal lobe (AF8, AF9) and two channels in the temporal lobe (TP9, TP10) were collected through the headband (original Muse) for the EEG measurement, and the user could experience the VR space by wearing the headset (Samsung HMD Odyssey). The experiment was conducted by taking measurements using the EEG equipment and the VR equipment simultaneously, and the controller of the VR device was used to synchronize the two pieces of equipment. With this, it was possible to adjust the shape of the subject's position in the building. This approach also synchronized the two tasks of processing the EEG data measured over time. Furthermore, it was possible to accurately determine the time point of data that appeared in the EEG signal, the location of the building and the location of the subject in VR. Thus, it was easy to process data when the two data points were compared and analyzed after measurement was completed.

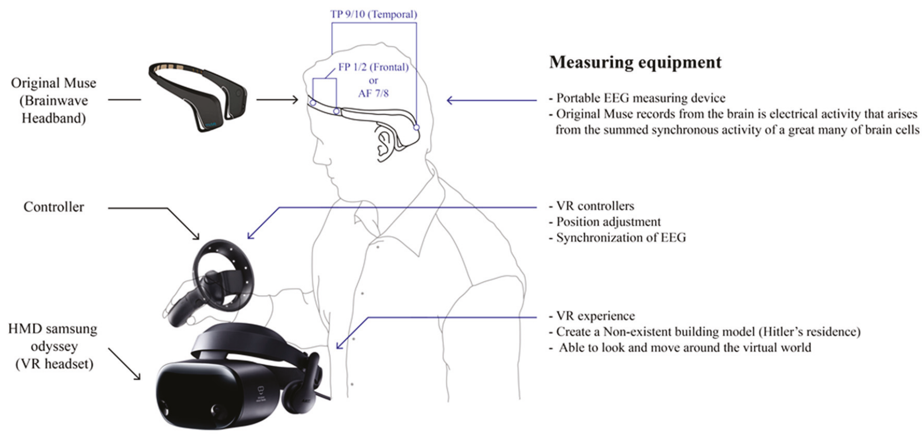

Figure 5. Experimental measurement.

3.3.2. EEG Experimental Method

The experiment was conducted on a designated long track in a stadium with sufficient space to prevent interference from surrounding elements during data measurement. Before starting the experiment, the subject was asked to assemble at a designated point for a smooth process and wait in place for several minutes to wear the experimental gear. The experiments of EEG measurement and data acquisition in the virtual space were conducted by directing the subject to simultaneously wear the Samsung HMD Odyssey VR headset and the Muse EEG data measurement headband (Figure 6). Once he was wearing the equipment, the virtual space of Hitler's chancellery reconstructed in Unity was connected to the VR equipment, and the Muse headband was linked to a smartphone to prepare for data measurement. After data measurement, the subject walked approximately 100 m inside the virtual building. The EEG signals generated while the subject passed through three different spaces were measured and collected.

The virtual space prevented the subject from deviating from the experimental path and guided the subject in the planned direction using virtual walls. The subject, however, was allowed to turn his head to any position to experience the VR space.

Figure 6. Experiment and measurement process.

Figure 7 shows the plan and elevation of the residence building reconstructed in the virtual space. The first space was a large courtyard called the Court of Honor. It was an open square space surrounded by 25 m tall walls and blocked from the outside, and only the ceiling was open to the sky. The second space that appeared when the subject passed through the Court of Honor was the Mosaic Hall, with a total height of 20 m and an interior space of approximately 15 m, which was nearly 10 m lower than that of the Court of Honor. There were no windows on the interior walls in the Mosaic Hall, and only an eagle-shaped mosaic statue with a torch decorated with oak leaves was displayed. Furthermore, the floor was made of smooth marble, off of which the ceiling was reflected, and the high ceiling directly above the floor had a translucent glass window so that the subject could feel somewhat cold when he entered the space [4]. After passing through the Mosaic Hall and the narrow passageway, the subject would naturally move to the 3 m tall bunker. As such, the subject passed through three spaces of 25, 15 and 3 m in height. The EEG signals generated according to the change in height of the indoor floor were measured and analyzed. To analyze the EEG data of the subject according to the measured spatial location closely, the EEG and VR image data were measured and compared simultaneously.

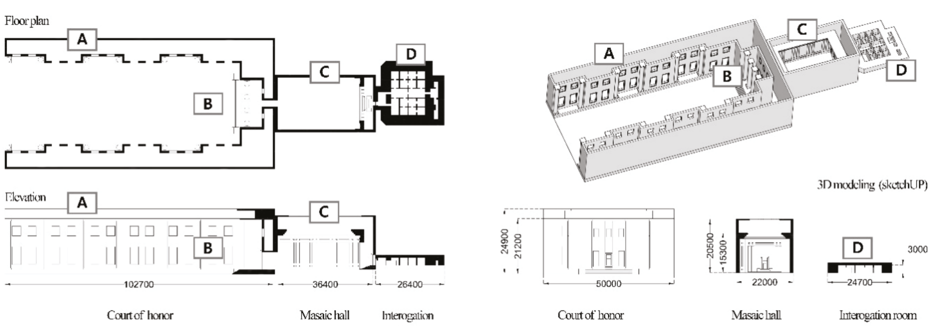

Figure 7. The Neue Reichskanzlei and three-dimensional orthographic projection ((**A**)—Court of honor; (**B**)—Court of honor and Mosaic hall transition space; (**C**)—Mosaic hall; (**D**)—Mosaic hall and Führerbunker transition space).

4. Experimental Results and Analysis

Two analyses were conducted in this experiment. In the first analysis, the results were ranked according to one type of beta wave to derive the point where the highest beta wave was generated, and the corresponding time information and VR information were recorded. In the second analysis, the point with high stress was derived by considering the correlation between the characteristics of waveforms using a deep-learning algorithm and all EEG data for alpha, beta, delta, theta and gamma waves.

The brain wave data analysis was performed using an offline postprocessing method instead of real-time implementation. The brain wave data were collected through VR and analyzed.

4.1. First Analysis (Beta Waves Only)

Muse, which is a brain wave measuring device, performed preprocessing of the raw EEG data using the Mind Monitor, which is a brain wave streaming application.

Among the embedded libraries of Mind Monitor, data on alpha, beta, theta, delta and gamma waves were extracted per frequency from the raw data of the EEG through independent component analysis (ICA). Then, the brain wave data from the subject were preprocessed for the first and second experiments.

The ICA extracted brain waves per frequency from the raw EEG data. Executing the ICA consisted of a total of four steps, of which steps 1 through 3 involved preprocessing for the ICA, and step 4 involved the actual execution of the ICA. Step 1 was the centering step, where the dispersed brain wave data were centered. The mean of the data was calculated and subtracted from the dataset, and the mean was reduced to 0. Step 2 was the whitening step, in which the dispersion in all directions and standard deviation were normalized and converted to a covariance matrix. Step 3 was the dimensionality reduction step, in which the dimensionality of data was reduced to remove unimportant data while maintaining the covariance matrix. Step 4 was the actual ICA step, in which the brain wave data from the EEG were extracted per frequency [36].

The ICA process separated reiterated brain wave data per frequency. The experiment was conducted using data organized based on each frequency from the sampling rate based on raw data to the mean data per second through an optimized process.

The data that underwent ICA per frequency were then used to deduce the priority of the stress index for spaces by implementing a deep-learning recommender system using Keras or TensorFlow among deep-learning frameworks instead of an RNN (Recurrent Neural Networks)-based long short-term memory algorithm [37,38].

Among the four types of EEG data collected through the Muse headband, except for the results near the temporal lobe, which are sensitive to auditory response, data were extracted based on the AF (Atrial Fibrillation) to analyze the measurement results.

The results were summarized, visualized and expressed using the visualization software Tableau [39,40] so that five types of EEG signals—alpha, beta, delta, theta and gamma waves—could be compared (Figure 8).

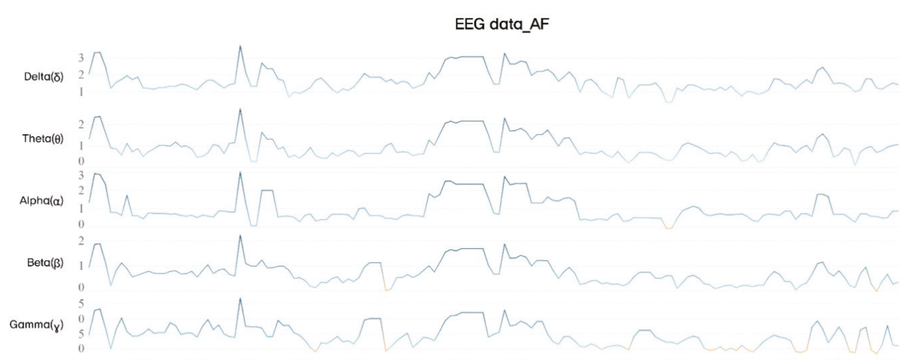

Figure 8. Visualization of EEG (AF) data.

Among the five measured EEG data types, the beta wave data, which are wavelengths that predominantly exhibit tension, excitement and stress, were analyzed separately (Figure 9). By plotting the beta wave data, we confirmed the increasing trend of the stress index of the subject in a specific space.

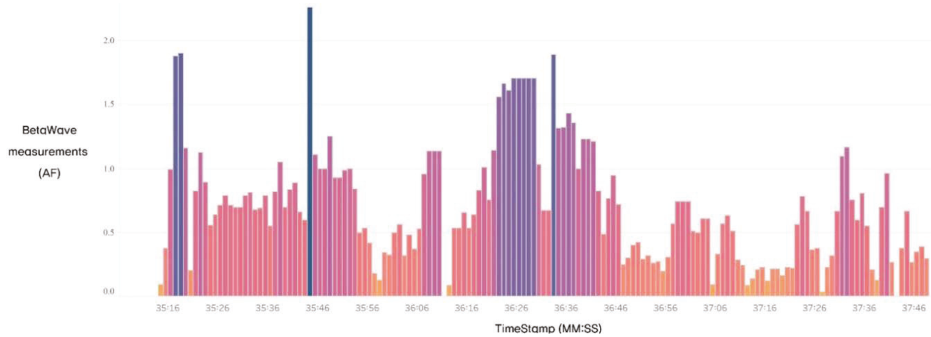

Figure 9. Beta wave visualization data.

To objectively find the space where the stress measurement values increased significantly with the largest change, the amount of change in each spatial dataset was calculated and analyzed as time-series data.

The resulting value was calculated from the beta wave data analyzed by comparing it with the recorded VR image data from the subject. The amount of change in the EEG data on the beta waves was visualized. The location of the space where the difference in stress variation was large was confirmed through the following drawings and graphs (Figure 10). The location could also be confirmed visually through the display on the right side of the VR space.

The results of the stress index change analysis were as follows: Because the amount of change immediately after the experiment could be extremely contaminated, data from this time were excluded (the remaining data are summarized in Figure 9). Thus, the stress change amount increased by +280% at 12:35:44, as shown in Figure 10A, and the stress index ranked fourth. The location in Figure 10A was the scene where the subject saw the magnificently arranged staircase and four huge pillars before entering the Mosaic Hall from the Court of Honor (corridor).

At 12:36:12, as shown in Figure 10B, the amount of change was +508%, showing the second-highest index change; this was the scene where the space changed from the Court of Honor (corridor), which was the largest space, through the narrow door leading to the Mosaic Hall.

At 12:37:05, as shown in Figure 10C, the scene where the subject entered the Mosaic Hall with a large wall mosaic decoration, smooth marble floors and high glass ceilings was depicted. It exhibited a +253.4% change. It was found that the stress index increased by +513.9% at 12:37:27 in Figure 10D, which was the part where the subject entered the bunker from the Court of Honor and showed the highest stress index during the experiment.

Finally, Figure 10E at 12:37:38 was the location where the subject stayed in the bunker-type narrow barrel cover, and the change was +435.5%. The results confirmed that the stress indices of the subject increased the most significantly when he was entering the bunker, which was a relatively low space, from a large space with a high floor height.

However, in the case of the first analysis, a partial method was used to check the amount of change by considering only one type of beta wave. Therefore, in the second analysis, a deep-learning algorithm was used to consider all the variables of the EEG signals to analyze the pattern and then find the rank of the section with high stress.

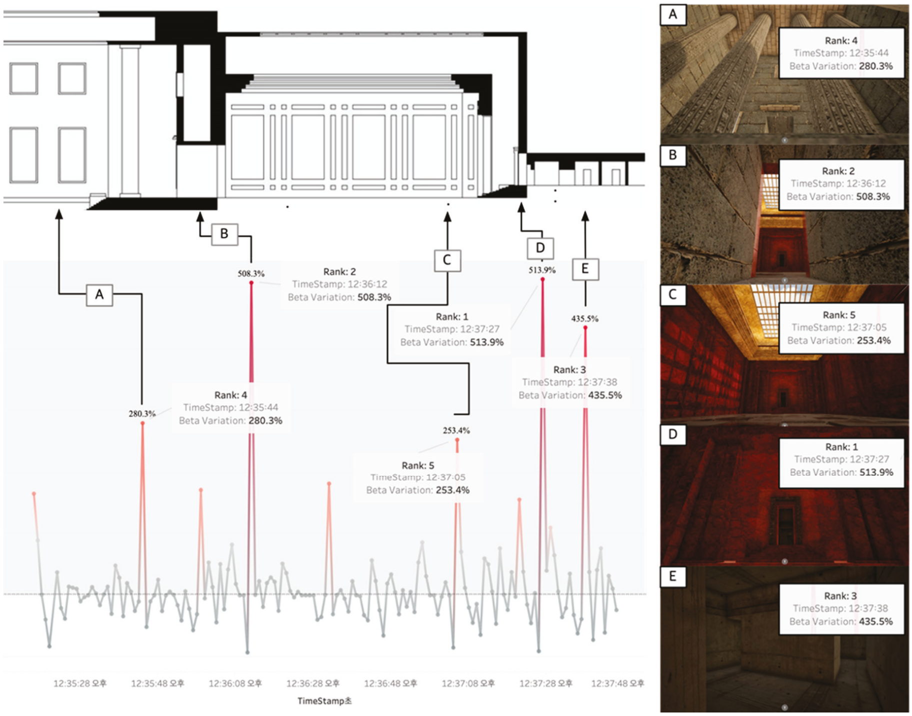

Figure 10. Beta wave variation graph and location ((**A**)—Court of honor; (**B**)—Court of honor and Mosaic hall transition space; (**C**)—Mosaic hall; (**D**)—Mosaic hall and Führerbunker transition space; (**E**)—Führerbunker).

4.2. Secondary Analysis (Alpha, Beta, Theta, Gamma and Delta Waves)

In the first analysis, a high beta wave value that matched the time-series information was calculated. First, to understand the correlation pattern among the collected EEG data, the flow of the pattern of data was analyzed using HiPlot, which was released by the Facebook AI team in early February 2020. HiPlot [41] is an AI interactive visualization tool that serves as a decision-making aid to identify correlations and patterns in data when using parameters with different characteristics before running the AI algorithm.

The graph shown in Figure 11 was expressed by arranging the range values according to the values of each requirement on the *x*- and *y*-axes on the 10 EEG parameters necessary for deep-learning training in this experiment. Figure 11 shows that the alpha waves (Alpha_AF7, Alpha_AF8) and beta waves (Beta_AF7, Beta_AF8) were inversely proportional to each other. Delta_AF7 and Theta_AF7 in the left brain position and Delta_AF8 and Theta_AF8 in the right brain position were also inversely proportional.

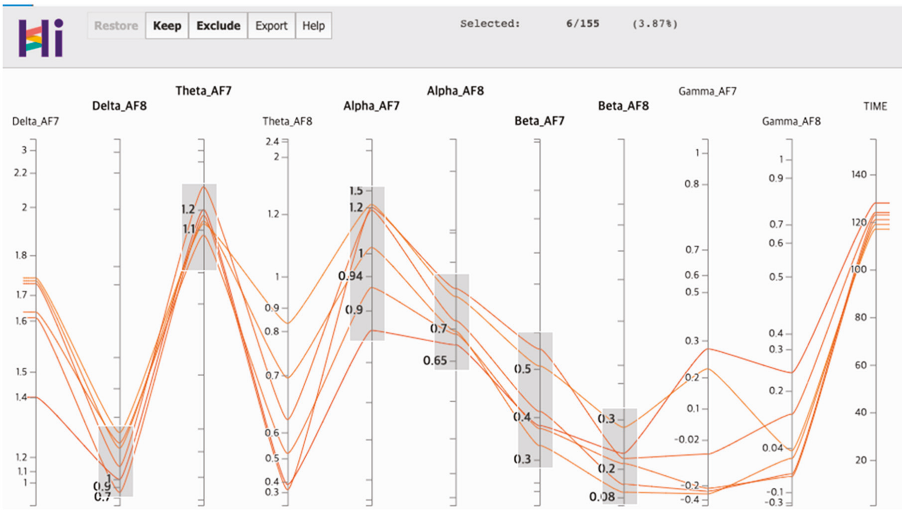

Figure 11. Correlation analysis of the EEG input data using HiPlot.

The general theory is that the beta wave is closely related to stress indicators. For example, when the stress indices of two cases are the same, if the stability index of one case is higher than that of the other case, the feeling of stress for the two conditions will be different. If the sense of stability is high and the stress index is the same, the subject will feel better than when the stability is low. This is called the stress ratio. Data with a low sense of stability and high stress tend to be more effective than finding a case where the stress index is only partially high. Therefore, based on the multivariable linear regression of deep learning, an algorithmic process was developed to calculate the priority of the stress index (Figure 12).

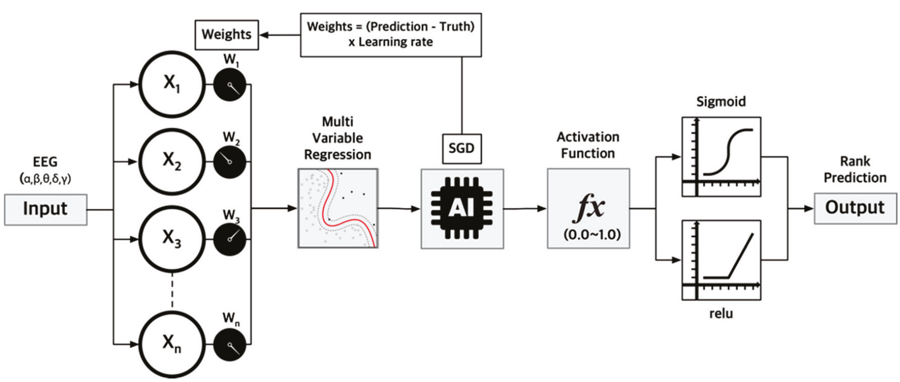

Figure 12. Process of the deep-learning-based algorithm to calculate the priority of the stress index.

In the next process, the SGD technique and the sigmoid activation function were used to find the region with high stress from multiple inserted parameter values. The SGD technique is an algorithm that calculates the difference between the predicted value and the actual value through deep learning and helps the model with high accuracy in weights. It is used to find the value of the optimal weight for implementing the multivariable linear regression effectively. We used a deep-learning algorithm to consider all 10 insertion variables of the alpha, beta, theta, delta and gamma waveforms of the

EEG signals. The sigmoid function is an activation function that can be compared to the ReLU (Rectified Linear Unit) function. It is used to generate results in percentiles between 0.0 and 1.0. The sigmoid function is mainly used for ranking tasks and classifying data, whereas the ReLU function is primarily used for predicting specific values based on past data patterns. We used this function because the experiment required the role of ranking in regions where the stress ratio for emotional information obtained from the EEG data was poor (Figure 13).

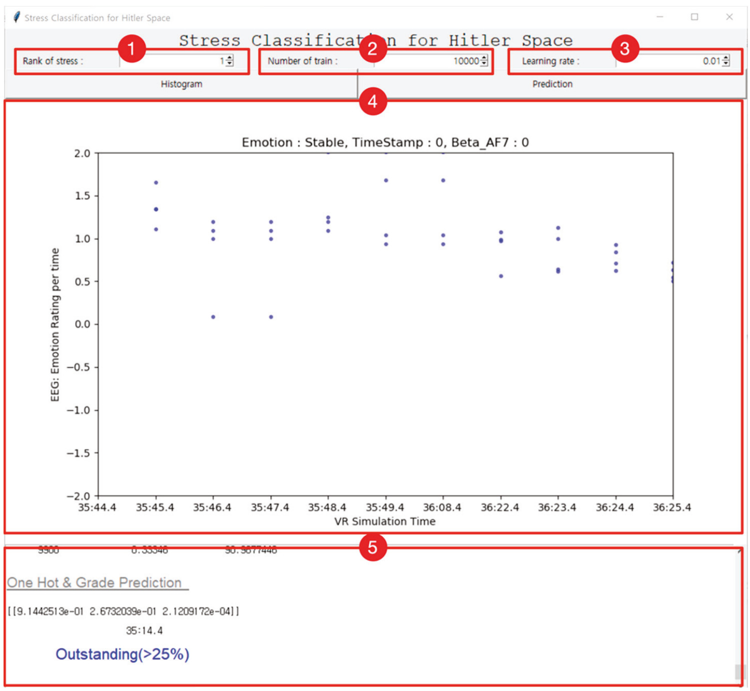

Figure 13. Deep-learning platform for calculating stress rankings for VR experience data.

① (Figure 13) determined the high-stress ranking, ② (Figure 13) was the number of training data points, and ③ (Figure 13) was a weight value that increased the accuracy during repeated training. ④ (Figure 13) was a scatterplot in which stress information was placed against time information on the x-axis. Based on the scatterplot, the deviation from the rest of the EEG information was used by the deep-learning algorithm to classify the worst time zone information, accuracy and distribution location according to the stress ratio in ⑤ (Figure 13). The stress was expressed as "outstanding (>25%)", "average (25–75%)" and "below average (<75%)". If the stress was high, it was expressed as "outstanding", and if the stress was in the region of less than 75% of the samples, it was expressed as "below average".

The accuracy gradually increased as the training progressed, and the final accuracy value was 90.96%. The number of iterations of the epoch, which indicated the number of trainings in the deep-learning model, was set to 10,000 times. As the number of times increased, the accuracy gradually increased, and the resulting value maintained the highest accuracy of the system after 9300 iterations (Figure 14).

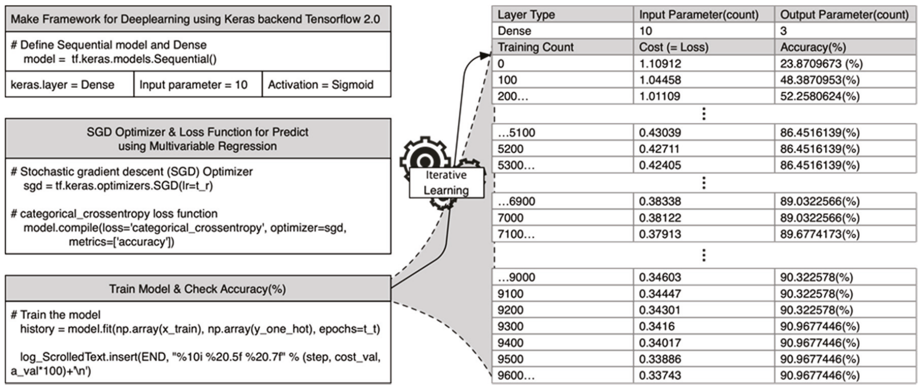

Figure 14. Primary deep-learning programming and training accuracy verification of the platform.

As a result of the first and second analyses of the emotional information from the EEG signals in the VR space, the amount of stress rapidly changed during the transition process of the space when only the beta wave was considered. The secondary analysis predicted the actual stress ratio through the correlation of parameters when alpha, theta, delta and gamma waves were used along with the beta wave. The results showed that the stress indices were intensely high at the entrance and at the beginning of the Mosaic Hall, and they ranked from first to fourth. In the case of the fifth rank, the corresponding index was obtained after the height of the floor in the bunker rapidly decreased (Table 1). Unlike the first analysis, the second analysis showed that the deep-learning algorithm understood and operated the correlation between the attenuated or increasing parameters according to the quantitative index of a positive waveform, such as the alpha wave. The stress index seemed to be concentrated in a specific space (Figure 15).

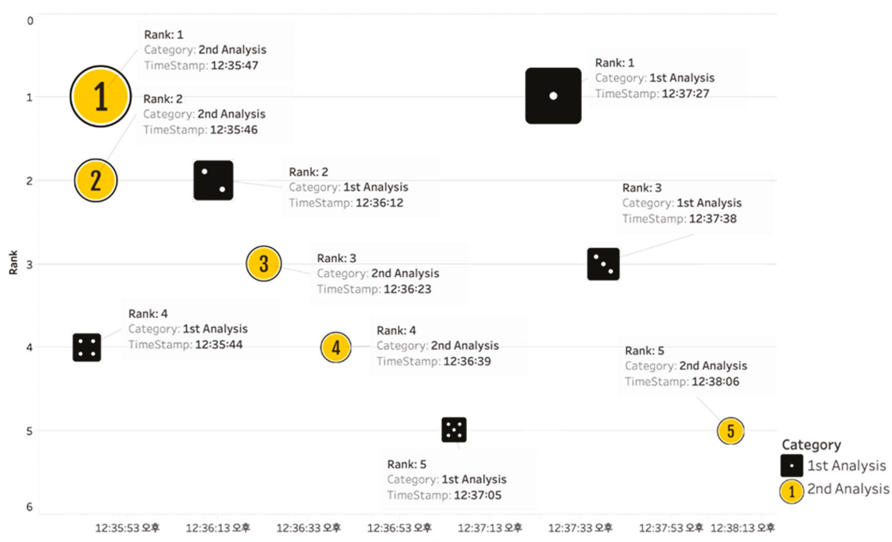

Figure 15. Comparison of the first and second analytical data.

Table 1. Comparison of the first and second analytical data.

Ranking	High Stress Time in First Experiment	Space Location	High Stress Time in Second Experiment	Space Location
1	12:37:27 p.m.	Mosaic hall and Führerbunker transition space	12:37:27 p.m.	Court of honor and Mosaic hall transition space
2	12:36:12 p.m.	Court of honor and Mosaic hall transition space	12:36:12 p.m.	Court of honor and Mosaic hall transition space
3	12:37:38 p.m.	Führerbunker	12:37:38 p.m.	Mosaic Hall
4	12:35:44 p.m.	Court of Honor	12:35:44 p.m.	Mosaic Hall
5	12:37:05 p.m.	Court of honor and Mosaic hall transition space	12:37:05 p.m.	Führerbunker

A *t*-test was performed to analyze the information on the net stress in the first and second analyses. The *t*-test results showed that the mean difference in the scores from the first and second analyses was −1.26, where the score in the second analysis was higher than that of the first analysis. The difference in the standard deviation was 0.0542. The paired sample *t*-test, which shows whether such a difference has a statistical significance, showed that the possibility of the null hypothesis for the first and second analyses being accepted was very low ($p < 0.001$); thus, the alternative hypothesis had to be accepted. It could be inferred that the net stress index from the second analysis improved with statistical significance when compared to that of the first analysis (Table 2).

Table 2. Comparison of *t*-test results.

Paired Samples *t*-test							
			Statistic	Df.	*p*	Mean Difference	SE Difference
First Analysis	Secondary analysis	Student's *t*	−23.2	154	<0.001	−1.26	0.0542

5. Conclusions

We analyzed the amount of stress change in a virtual space by reconstructing Adolf Hitler's Neue Reichskanzlei (translation: New Reich Chancellery) using VR, synchronizing VR equipment and measuring the EEG signals. The virtual chancellery was composed of three spaces with different floor heights—the Court of Honor, the Mosaic Hall and the bunker. Subsequently, an EEG experiment was conducted to help the subject experience the virtual building while measuring the EEG signals from the subject and collecting data. Using the acquired EEG data, data were preprocessed by considering the characteristics of big data, and two analysis methods were used to analyze the emotional state and identify regions with high stress. The following conclusions were drawn:

- The results of similar data demonstrated that the building was indeed designed to induce feelings of grandiosity and trepidation and that the feelings experienced by the president of Czechoslovakia, who had a heart attack in the residence, were obtained.
- The results of the stress index analysis based on the EEG data revealed that when the subject sensed changes in pressure in the high floor space as he moved from a higher floor to a lower floor, he experienced changes in space, which were reflected by an increase in the stress index, indicating that the subject was in a psychologically tense state.
- Comparing EEG data from the subject moving from the Court of Honor with a 25 m tall floor to the Führerbunker with a 3 m tall floor, the total intensity of the beta wave, which is related to stress, was found to be relatively large when the spaces changed. The graph of the experimental results showed that the most significant change in stress was observed when the subject entered the Führerbunker, with a 3 m high floor, from the Mosaic Hall, with a 15 m high floor, owing to these spaces having the largest floor difference.
- Two methods were used to analyze the emotions that the user felt in the VR space based on the EEG signals: a method of expressing unpleasant regions according to time information based on the beta wave that represented stress among the EEG signals and a method of operating deep learning to predict the stress ratio through a correlation analysis of all EEG signals by ranking the

regions according to the level of stress. A comparison of the results of the two analysis methods revealed different results from each datum. The first analysis showed that the amount of changes in the beta wave index were high during spatial transitions. In the second analysis (stress ratio analysis), the index was found to be high in the spatial transition at the entrance to and inside the Mosaic Hall. Particularly notably, the corresponding index was high in the space where the subject entered a 15 m high floor through a narrow entrance. Both results were meaningful for analyzing an architectural space. However, in the VR space, we found it necessary to analyze the positive indices through the linking process of the EEG signals or the stagnation of pupils on certain architectural design elements. Therefore, in future research, a VR experiment of a building space must be performed by fusing eye-tracking equipment with VR and EEG equipment. Accordingly, the effective pattern must be calculated by integrating the process for data collection by the sensors of each piece of equipment through integration with deep learning.

Furthermore, to minimize physical contact between the EEG and VR gear during experiments where several pieces of equipment are used simultaneously, research and development must be conducted by constructing a combination of two pieces of equipment, an HTC Vive with EEG sensors, inside the VR head strap. Additionally, to allow for data stabilization, EEG measurements must be conducted using gel-type sensor nodes. Instead of the example in this study, a domestic place such as the National Intelligence Service's anticommunist room, which is a representative site of dark tourism that can be experienced in a space in reality, must be used. By selecting such a place, the elements of each space and the human sensibility felt in that space can be compared in a future study.

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Article

"SeoulHouse2Vec": An Embedding-Based Collaborative Filtering Housing Recommender System for Analyzing Housing Preference

Han Jong Jun [1], Jae Hee Kim [1], Deuk Young Rhee [2] and Sun Woo Chang [2,*]

1 School of Architecture, Hanyang University, Seoul 04763, Korea; hanjong@hanyang.ac.kr (H.J.J.); jehee1122@hanyang.ac.kr (J.H.K.)
2 Garam Architects & Associates Research and Development Center, Seoul 06037, Korea; bluearchitect@naver.com
* Correspondence: workingholid@hanyang.ac.kr; Tel.: +82-2-2017-6637

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Abstract: Housing preference is the subjective and relative preference of users toward housing alternatives and studies in the field have been conducted to analyze the housing preferences of groups with sharing the same socio-demographic attributes. However, previous studies may not suggest the preference of individuals. In this regard, this study proposes "SeoulHouse2Vec," an embedding-based collaborative filtering housing recommendation system for analyzing atypical and nonlinear housing preference of individuals. The model maps users and items in each dense vector space which are called embedding layers. This model may reflect trade-offs between the alternatives and recommend unexpected housing items and thus improve rational housing decision-making. The model expanded the search scope of housing alternatives to the entire city of Seoul utilizing public big data and GIS data. The preferences derived from the results can be used by suppliers, individual investors, and policymakers. Especially for architects, the architectural planning and design process will reflect users' perspective and preferences, and provide quantitative data in the housing decision-making process for urban planning and administrative units.

Keywords: embedding; recommender system; collaborative filtering; housing preference; housing decision

1. Introduction

Seoul is the capital of South Korea, with a population of approximately 9.7 million people [1]. Of the 605.24 square kilometers of land in Seoul, 53.8% is designated as residential areas. Furthermore, based on household—Korea's unit of housing—about 2,866,000 houses have been supplied, a housing supply rate of 96.3% [2]. Housing affects occupants' health, wealth, and lifestyle as it provides the necessary built indoor environment in which they live for an extended period. In addition, housing-related costs including the purchase and lease of housing account for a significant portion of household spending [3]. From a social viewpoint, housing helps form and maintain relationships with occupants' families, friends, and communities, thus impacting their well-being [4–7].

Housing decision-making is a process in which users explore and evaluate housing choices by considering housing attributes including tenure, type, size, orientation, location, etc. [8,9]. Through this process, users form subjective preferences for certain housing alternatives [10–12]. Housing choice is expressed in actual behavior regarding the housing unit, and housing preference is the relative preference for housing alternatives [13,14]. Based on their economic and social contexts, users form housing expectations and preferences in the process of housing decision-making [15]. While housing choice is significantly affected by users' housing preferences, it may differ from these because of real-world constraints such as the market price of housing and government regulations. The resulting choice, as revealed in actual behavior, is termed revealed preference, and the user's original preference is the stated preference [10]. Even with the fact that the stated preference may be different from the revealed preferences, the studies have been conducted in a way to suggest factors that affect the preference and to provide rational basis in the process of housing choice. The studies were also meaningful in that from the perspective of architects, construction companies, and the government, who are the suppliers of housing, the decision-making process related to housing planning and design in architecture and urban scale can be carried out under more reasonable and less risky conditions. An increasing number of studies have been conducted alongside the increasing importance of reflecting users' perspective in the planning and design phases [16–21].

In recent studies according to housing preference, Hoshino [22] dealt with 10 housing attributes with details of residences and location such as building age, building class, transportation, and land use; then, Mulliner (2018) addressed three categories of attributes which are extrinsic factors (quality, age of building, lot size, etc.), intrinsic factors (e.g., heating, ventilation, and air conditioning and insulation), and location and environment (neighborhood safety, cleanliness, etc.) [23]. Additionally, Jancz (2020) addressed eight housing attributes related to users' lifestyle such as social factors, building type, environment, communication, neighbors [24], and Wang et al. [25] also addressed five categories of attributes including product, price, place, promotion, people using fuzzy analytic hierarchy process.

A recent study quantitatively derived variables that affect respondents' housing preference. The study suggested the correlation between socio-demographic attributes of the respondents—age, income, values, etc.—and the housing preference variables using statistical techniques. This calculates the relative importance of housing preference variables for groups that share specific demographic attributes [22,26,27]. Furthermore, studies have derived housing preference variables, elicited and quantitatively measured them, and analyzed the process in which these preferences are formed for a particular group. However, these studies were limited in terms of analyzing the housing preferences of individual users, as the unit of analysis was groups that share particular socio-demographic attributes. Thus, they could not explain the preferences of users who belong to that group but have different preferences.

Therefore, a recommendation system that analyzes user data, such as purchase history, viewing records, and ratings to derive unstructured preferences and select and present items that users might prefer, is now gaining attention [28,29].

Among the methods of implementing the recommendation system, collaborative filtering technology has recently demonstrated high accuracy. It measures the similarity between items or users based on data on the user's rating of the item. Based on the assumption that users with similar preferences for certain items would have similar affinity responses for other items, it presents users with items they might prefer [30]. The method of measuring similarity in the recommendation system uses machine learning-based methods such as K-nearest neighbors and naive Bayes classifiers, although studies have been conducted that utilize embedding technology. Embedding technology is a technique for mapping individual items to n-dimensional vector space, and the more similar the meaning or attributes of individual items in the mapping process, the closer the geometric distance between them [31]. In the recommendation system, item-to-item or user-to-user similarity can be expressed as numeric vector distances, which are called item embedding and user embedding [32]. In the recommendation process, if a particular user prefers a particular item, the recommendation will be made sequentially by presenting items located in a close distance. An earlier study contended that the embedding-based recommender had a higher accuracy and faster learning speed than other implementation methods, and other research showed that it could visually present similarities between items or users [33,34].

The purpose of this study was to build an embedding-based collaborative filtering recommender called "SeoulHouse2Vec." The model works by mapping users and items to each low-dimensional dense vector space based on user-item rating information obtained through a survey. For this purpose, a housing preference survey was conducted, the results of which were used to build a dataset consisting of rating information on multiple housing profiles of individual respondents. Recommended housing alternatives are presented to users using geographic information system (GIS) and data visualization technology. While previous housing preference studies were conducted by calculating the relative importance of variables and variables affecting the housing preferences of groups with the same demographic and sociological attributes, the analysis unit of this study was the individual, which is a smaller unit. Through this, the study presents one way to support users' search for housing alternatives and their housing decision-making process.

Research Materials, Methods, and Structure of the Paper

The paper is organized as follows: Section 2 highlights theoretical considerations regarding the housing preference and the embedding-based collaborative filtering recommendation system. As explained, housing preference variables that affect the housing decision-making process in Korea were derived from an analysis of existing research. In Section 3, public data based on the housing preference variables derived from the preceding step are used to create housing profiles subject to survey respondents' preference. Respondents rated their preferences for the housing profiles in the survey. In the process of creating the profiles, "Seoul Metropolitan Government Housing Status (housing type, occupancy type, etc.) Statistics" [35], "Seoul Metropolitan Apartment Information" [36], and GIS location information data were used. Section 4 describes user-item rating datasets acquired through the survey and, using Google TensorFlow and Keras, builds the "SeoulHouse2Vec" recommendation system. In Section 5, the dataset acquired in the previous step is split into training, validation, and evaluation sets. The split datasets were used to the corresponding process, respectively. In the model training, a supervised-learning method was used. After that, the model validating in which the model parameters are tuned for better performance is conducted. The final performance is then measured using performance metrics, which are precision, recall, and f1_score. To measure the metrics, a confusion matrix, which is a commonly used method in the algorithm evaluation, is created. This study uses Python 3.6, Google TensorFlow, and the Keras library to build the model in Section 4. In Section 5, the built model is trained, validated, and evaluated. The development environment is set to JetBrains Pycharm Community Edition 2019.1.2. The hardware environment is "Intel i9-9900k" CPU, 16 GB RAM, and "NVIDIA GeForce RTX 2060," with Windows 10. In Section 6, scenario-based demonstration of the built model is suggested in order to provide a possible application of the model in terms of analyzing housing preference and supporting housing decision-making.

Figure 1 presents the research overview, which comprises three parts: Dataset generation, "SeoulHouse2Vec" model building & training & evaluation, and model application & visualization.

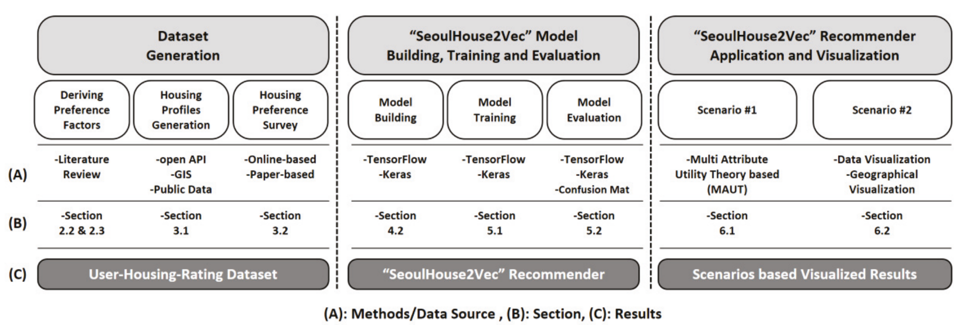

Figure 1. Research overview.

2. Literature Review

2.1. Embedding-Based Collaborative Filtering Recommender System

The recommendation system filters preference information and supports their information search process. Its value has recently drawn interest because it can help users when considering increasing volumes and types of information [28,37]. Methods for running the recommendation system include the bestseller presentation method, which presents items with a large number of views over a specific period, and content-based process, which manually extracts and analyzes the attributes of an object. Recently, studies have confirmed the relatively high accuracy of a technology called collaborative filtering [38–40].

The premise of collaborative filtering is that groups of users with similar preferences for specific information will have similar responses to other details. Unlike the content-based method, where recommendations are based on the extracted internal attributes of items, the collaborative filtering method utilizes rating information, which is the preference information obtained from multiple users' evaluation of multiple items. The significance of the collaborative filtering method is its "collaboration," as it uses users' ratings to recommend items to a specific user [28,41,42].

Among the various methods of implementing the collaborative filtering-based recommender, embedding-based methods have attracted attention for their accuracy and efficiency [33,34,43]. For Guo and Berkhahn [44], embedding is a technology that represents non-continuous data in the sparse vector format as continuous data in the dense vector format. Embedding technology derives the intrinsic properties of data by continuously providing the right representation thereof and supporting the learning process of machine learning and deep learning models. Guo and Berkhahn [44] showed that when input data are embedded in the right way, terming it "entity embedding," the training speed of the artificial neural network model increases, and decreases overfitting. The data are finally placed in Euclidean space in a way that minimizes errors in the neural networks model [45].

Embedding technology has most recently been used in the field of natural language processing, a technology that allows computers to understand the natural language in a process called word embedding. In word embedding, natural language tokens (minimum unit of the data) are expressed in a dense vector consisting of floating-point values [46,47]. As the training iterations of word embedding and natural language processing model are repeated, the more similar the semantic meanings of the natural language input units, the closer those are mapped in the embedding space. The semantic relations of the natural language are thus expressed in a format the computer can execute, which is called distributed representations of words.

In the embedding-based collaborative filtering recommendation system, the natural language tokens, which are subject to similarity calculation in the word embedding technology, are cast as individual users and items [48]. Prior research on the embedding-based collaborative filtering recommender include studies [31] on building the embedded technology-based music recommendation system "ITEM2VEC"; a personalized e-mail advertising system called "prod2vec," which is based on user purchase records [49]; "prefs2vec," which is based on users' item preference [43]; and a system based on users' visit record ("the check-ins"), which recommends places users might like to visit [33].

Various studies suggested that an embedding-based recommender makes it easier for users to intuitively and visually identify similarity than other implementation methods. Furthermore, its simple model construction and higher learning efficiency are highlighted.

This study aims to build a recommendation system using embedding-based methods to provide the housing profiles users might prefer, and to visually suggest similarities between the users and the housing alternatives.

2.2. Housing Preference

Housing preference is the users' subjective evaluation toward housing. It refers to the users' requirements, expectations, and emphasis on the characteristics of various housing.

Studies related to housing preference analyze the housing preferences and design requirements of specific groups that share socio-demographic attributes including age, gender, income level, current values, etc. to provide one possibility to improve design quality and increase occupants' satisfaction [24]. The studies have provided basis to guide future design decision-making for architects and enable a quantitative comparison and evaluation methods between housing alternatives when choosing housing for potential users and occupants.

Opoku and Abdul-Muhmin [26] analyzed the correlation between socio-demographic attributes—gender, marital status, income, family situation, etc.—in Saudi Arabia's low-income class, and multiple kinds of housing factors including dwelling type and tenure options. Contending that the preference is heterogeneous, Hoshino [22] created housing profiles by deriving housing attributes and levels, and analyzed user preferences through a conjoint analysis method. Jansen et al. [10] studied a housing selection scenario for couples, presented multiple dwelling profiles on the basis of housing attribute levels (dwelling type, costs, size living room, number of rooms, backyard size, architectural style, and residential environment), and used the multi-attribute utility method to analyze housing preference and calculate the utility value, which can be used to recommend and analyze the choices. They also presented a unit consisting of the preferred factors of a group with specific socio-economic attributes.

Together, previous studies identified factors that affect housing preferences, designed questionnaires, and measured the correlations between respondents' social, economic, and demographic attributes and other factors. However, these studies were limited in terms of analyzing individuals who share common demographic attributes but have different preferences, or conversely those with dissimilar demographic attributes but the alike preferences. While providing one possibility for quantitatively assessing the alternatives by weighting factors, they are limited in giving trade-off or unexpected alternatives for various attributes, despite that users' preferences for the options are heterogeneous and nonlinear.

Thus, this study derived housing preference variables from prior studies and used them to quantitatively induce users' preference for housing alternatives. The collaborative filtering-based recommendation system was then used to analyze the preferences. Through this process, a recommendation system was created that can present divergent housing alternatives users may prefer.

2.3. Important Housing Attributes for Housing Preference in South Korea

Although research on housing preferences is actively conducted in various countries, the scope of this analysis was limited to papers published between 2009 and 2020 in Korea because of differences in housing preference variables by region and age.

The studies by Jeong and Choi [6] and Kim and Seo [50] are considered significant. They studied the housing choices and preferences of the eco-generation and baby boomers, deriving variables specific to these generations. Jeong and Choi [6] identified the local status of housing demand/development potential, educational environment, location factors related to public institutions/facilities, and green areas and rest areas as essential factors the eco-generation considered when choosing homes. Kim and Seo [50] identified the variables of housing preferences as social, local, and personal factors affected by friendliness toward the elderly; physical factors including housing styles and size; and economic factors including housing prices, rent, and housing costs.

Lee and Kim [7] and Lee, et al. [51] studied, quantified, and determined the importance of residential environment preferences through a conjoint analysis. However, their studies were limited in that the survey was conducted as a hypothetical alternative that arbitrarily manipulated residential variables. Thus, they were not able to use actual residential options. As Table 1 shows, Lee and Kim [7] examined the impact of apartment environmental attributes on consumer preferences by employing the variables of apartment prices, house interior factors of scale, investment value of brand awareness, view, and park accessibility. Lee, et al. [51] employed the extant literature and criteria for calculating the initial sale rate of apartments provided by the Korea Housing & Urban

Guarantee Corporation to identify the variables impacting housing preference, as shown in Table 1. The variables for housing preference were housing characteristics and price per 3.3 square meter including of the interior, characteristics of the complex, convenience of transportation, location in the city center, environmentally friendly location, location in a good school district, potential for regional development, and investment value.

To identify housing preference variables according to lifestyle, Son and Lee [52] delineated apartment complexes and indoor requirements by considering the actual living space and experience rather than location of housing from a macro perspective.

To analyze housing satisfaction and preference, Kim et al. [53] examined changes in preference according to the type of housing, type of occupancy, and size of housing in Gyeonggi Province; identified factors to consider in housing policies; and explained differences in housing demand by region. The variables were housing location factors including the convenience of public transportation, neighborhood facilities, cultural performance facilities, accessibility to major facilities, and children's educational environment. The internal factors included size and management expenses, and environment factors included green areas and nearby parks as well as investment value.

Lee and Kim [7], Kim and Seo [50], and Lee, et al. [51] quantitatively measured preference by demonstrating the correlation between housing attributes and housing preference, as well as between respondents who share specific socio-demographic characteristics such as age (generation), gender, type of residence, type of housing tenure, and income. The outcome of these studies was models showing how much a particular group values a specific factor. However, they did not offer a real housing alternative or housing suggestions because they do not reflect atypical preferences.

Thus, the present study used a real housing profile to analyze accumulated housing preference data. Furthermore, it recommends unexpected housing alternatives that reflect atypical preferences by building an embedding-based collaborative filtering recommender to support users' decision-making process. The preferences derived from the results can be used by suppliers, individual investors, and policymakers [54]. Table 1 summarizes the key aspects of the literature review.

Table 1. Literature review of the housing attributes for the housing preference in South Korea.

Reference	Research Purpose	Research Method	Housing Preference Variables
[6]	Explores important factors of newly married eco boomers' house selection	Multiple linear regression analysis	Housing location, housing facilities, eco-friendliness, educational environment, living convenience, residential safety, residential status, economic power, family
[53]	Investigates lifestyle demographic characteristics and analyzes the effects on characteristic factors of apartment housing preference	Pearson correlation, regression	Location of educational facilities, location of commercial districts, apartment exterior, apartment functions, community within the complex, interior design, interior, indoor function, privacy, storage space
[51]	Studies the influence of view quality and park accessibility on consumers' apartment preference to determine implications for revitalizing apartment marketing	Conjoint analysis	View, size, park accessibility, apartment prices, brand awareness
[42]	Identifies factors to consider in future housing policies and explains differences in housing demand by region	Binary/multiple logistics regression	Housing size, housing facility level, noise, odor, management status, green area facility, convenient facility within complex, air and water quality, surrounding facilities, cultural performance facilities, public transportation convenience, security, access to major facilities, neighborhood parks, children's educational conditions, management costs, relationship with local residents, housing investment value
[50]	Establishing future housing policies and marketing strategies based on the housing preferences of baby boomers	Technical statistics and cluster analysis	Social factors (leisure activities, relationships with friends and neighbors, composition and community level of neighbors), location factors (ease of use of elderly services, safety, cleanliness of surrounding area), personal factors (physical function, distance from children), physical factors (housing style, housing size), economic factors (housing price/rent, housing costs)
[51]	Providing predictive data to meet the diverse needs of consumers and improve their residential value	Conjoint analysis	Price per 3.3 square meters, housing characteristics, complex characteristics, location, investment value

3. Survey Design

3.1. Housing Attributes and Housing Profiles Composition

Based on the literature review on the housing preferences, discussions with certified architects and housing planning and design experts, and in-depth interviews with occupants of apartments, this study derived the following nine attributes: "time to metro," "accessibility to market," "number of schools," "housing prices," "housing area," "number of rooms," "number of bathrooms," "distance to park," and "investment value."

The housing profiles are housing alternatives prepared based on the abovementioned nine housing preference variables. Those were presented to respondents through a survey. Respondents considered all nine variables and evaluated their preference for the profiles on a scale ranging from 1 (least preferred) and 5 (most preferred). Before creating the housing profiles, 30 pilot profiles were designed to modify the scope and definitions of some criteria. Below, the final nine variables are defined and the creation of the profiles are explained.

First, "time to metro" was measured by walking time (minute) to the nearest subway station. It refers to the accessibility to public transportation. There are two types of public transportation in Seoul: bus and subway. In designing the pilot profiles, the time taken to the nearest bus stop was about less than five minutes. As there was no significant difference between the apartments, the criterion was based on the time required to the nearest subway station on foot.

Second, "accessibility to market" is the distance to the nearest store from the specific profile which is related to proximity to the commercial districts. In preparing the pilot profiles, the distances from the specific apartments to the nearest convenience stores were not discriminating factor in Seoul. In this regard, the measurement used the "large market search" function provided by Naver Maps, which is commonly used in Korea. Due to the size and visiting characteristics of department stores, big-box stores, etc. most people use vehicles rather than walk to get there. The distance traveled in meter units was used to exclude the effects of travel time depending on traffic conditions.

Third, "number of schools" measured the number of elementary, middle, and high schools located within a 1-km radius from the apartment.

Fourth, "housing price" is the price of the apartment divided by "a unit *pyeong(3.3 m2)*". The prices are referenced and created based on the "Multi-unit Housing Handbook" (2005.1.1–2019.6.1). The unit of this factor is 10,000 Korean Won (KRW). The price used in this research was hypothetical since there were gaps between actual market prices and official prices given by the government ("Gongsiji-ga") for housing taxes. Moreover, since the market price may differ from time, district, market situation, government policies and cases, this study used hypothetical price referenced by the statics [54].

Fifth, "housing area" was also based on the "Multi-unit Housing Handbook" (2005.1.1–2019.6.1). The criteria for area were based on the "jeon-yongmyeonjeog (exclusive area)" of rooms, living rooms, bathrooms, and kitchens used only by the apartment unit. Thus, public areas in the apartments were excluded, such as stairwells, corridors, and community facilities [54].

Sixth, "number of rooms" reflects the number of rooms inside the unit excluding living rooms and kitchens.

Seventh, "number of bathrooms" reflects the number of bathrooms inside the unit.

Eighth, "distance to park" was measured on the map from the house to the nearest park to determine environmental factors. The unit is meter.

Finally, "investment value" was used to determine investment value. The investment value of apartments was assumed to be have for Samsung, Hyundai, Daelim, GS, Daewoo, POSCO, Hyundai ENG, Lotte, HDC Hyunsan, and Hoban Construction, the top 10 domestic construction companies in the "Construction Capability Assessment (2014–2019)" provided by the Ministry of Land, Infrastructure and Transport. For other cases, it was assumed there was no investment value [51,55].

The housing profiles were limited to the Seoul. Housing type was limited to apartment with five or more floors following "Article 3 clause 1 no. 1 of the Enforcement Decree of the Housing Act and Article 3–5 of the Enforcement Decree of the Building Act" [56,57]. According to the "Integrated Apartment Information Center," there are 3368 apartment complexes in Seoul. Thus, to ensure a 90% confidence level, 722 housing profiles must be created. However, 679 profiles were created because of missing data and problems pertaining to overlapping. Table 2 summarizes the nine variables and units derived from the literature review and their criteria.

Table 2. Nine housing attributes used to create the housing profiles.

No.	Item	Criterion (unit)
ATTR#1	Time to Metro	Walking distance to the nearest subway station (minute)
ATTR#2	Accessibility to Market	Distance to the nearest supermarket (meter)
ATTR#3	Number of Schools	Number of educational facilities within 1 km
ATTR#4	Housing Price	Prices of the created profiles (10,000 KRW)
ATTR#5	Housing Area	Housing area (m^2)
ATTR#6	Number of Rooms	Number of rooms excluding living rooms and kitchens
ATTR#7	Number of Bathrooms	Number of bathrooms
ATTR#8	Distance to Park	Distance to the nearest park (meter)
ATTR#9	Investment value	Ranked in top 10 construction capacity (yes/no)

Figure 2 shows a Box and Whisker plot for the 679 housing profiles based on 6 of the 9 variables: time to metro, accessibility to market, number of schools, housing price, housing area, and distance to park.

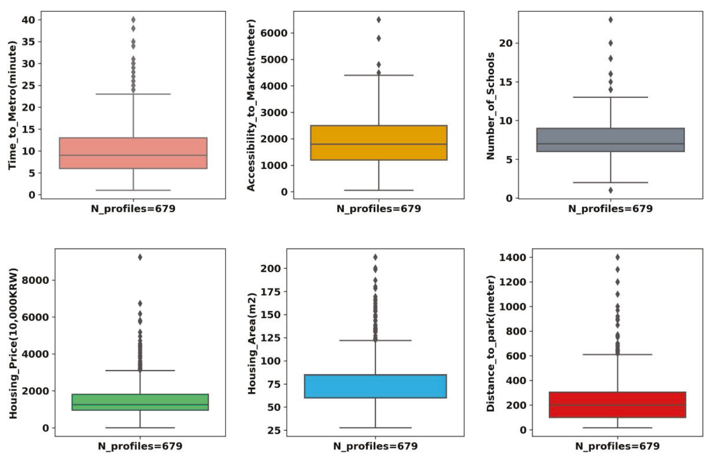

Figure 2. Data description of the acquired 679 housing profiles based on the six attributes.

3.2. Survey Design

In this study, respondents aged between 20 and 60 years were surveyed for 5 months between 1 October 2019 and 29 February 2020. The survey was conducted offline and online in a way that did not create differences between the two methods in content or presentation. In total, 100 copies of the questionnaire were distributed offline and 150 online, and 233 were retrieved: 98 offline and 135 online.

The questionnaire consisted of questions relating to respondents' socio-demographic attributes including their age, monthly household income, and housing tenure type, and those measuring their ratings of the profiles. In total, 30 randomly extracted profiles were given to the respondents, and three profiles formed a combination. These were presented to users 10 times. This number was determined in advance through the pilot survey process to ensure the survey secured a reasonable amount of data but did not fatigue respondents.

4. "SeoulHouse2Vec" Model Building

4.1. Dataset of Housing Prefernces Ratings Description

Of the 233 questionnaires retrieved, 18 respondents who gave incomplete responses or had missing information were excluded, resulting in 215 surveys. The dataset built through this consisted of 6450 (215*30) rows. The dataset consisted of the following: "UserId," a unique six-place identification code (three alphabet letters + three digits) to ensure the anonymity of survey respondents; "HousingId," which is subject to a preference evaluation; "Rating," which is the rating the user gives for the housing profiles; and respondents' socio-demographic attributes. The attributes were not used when training the embedding-based recommendation system model. Dataset consisted of rows and ratios of 2568 (39.8%), 1883 (29.2%), 920 (14.3%), 748 (11.6%), and 331 (5.1%), respectively, based on a rating of 1 to 5. Further research is needed on the fact that relatively unfavorable ratings (1–2) accounted for a large portion of the data. For the socio-demographic attributes, of the 215 people, 88, 27, 21, and 79 participated in the dataset for the age groups 20 to 30, 30 to 40, 40 to 50, and 50 to 60 years, respectively. Based on monthly household income, 50, 36, 19, and 110 people participated in the income groups of less than 2 million KRW, 2 to 3 million KRW, 3 to 4 million KRW, and 4 million KRW or more, respectively. Type of housing tenure was divided into three categories: self-owned, "Jun-se" (Korean unique lease type), and monthly rent, with 125, 50, and 40 respondents in each group, respectively. Figure 3 shows the distribution of respondents' socio-demographic attributes and ratings based on age, monthly household income, type of housing tenure, and rating.

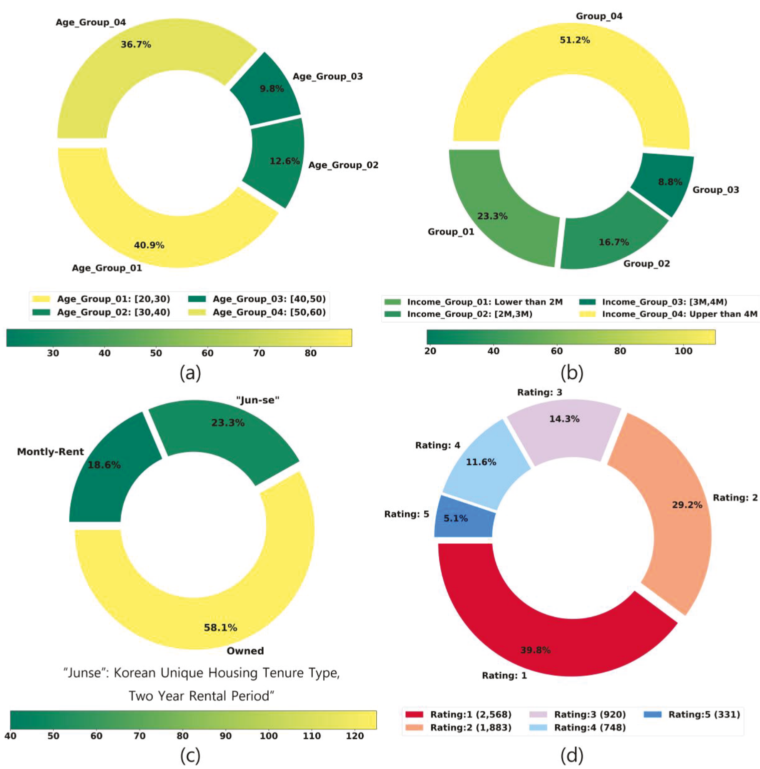

Figure 3. Acquired questionnaire data description (**a**) by age, (**b**) monthly household income, (**c**) housing tenure type, and (**d**) rating.

4.2. Model Structure

In the data pre-processing phase, label encoding was performed for UserId and HousingId. In total, 215 existed for UserId and 679 for HousingId; thus, they were expressed as unique index values ranging from 0 to 214 and 0 to 678, respectively. Label encoding used the "LabelEncoder" function provided by "scikit-learn" API. Through label encoding, string-type data are expressed in numeric format and entered into the model. For "Rating," one-hot encoding was conducted, which represents N number of data as sparse vectors in N-dimensions. This process expressed 1, 2, 3, 4, and 5 as [1, 0, 0, 0, 0], [0, 1, 0, 0, 0], [0, 0, 1, 0, 0], [0, 0, 0, 1, 0], and [0, 0, 0, 0, 1], respectively. One-hot encoded rating values are frequently used in the process of expressing the class and prediction in the classification model.

This model has two input layers, which receive as input values UserId and HousingId to calculate the similarity between users and housing items at subsequent embedding stages.

Embedding layers are the core layers that make the recommendation system operational. They map the encoded UserId and HousingId data to n-dimensional dense vectors. The embedding dimension is the dimension of a dense vector, for which a larger number represents a higher dimension. The vector values present in n-dimensions place individual data in the space in a way that minimizes the errors that are the difference between the model's prediction and the actual rating (Rating) as the training repeats. In this process, the users' atypical preference for the profiles is expressed in the dense vector space in the form of computational data.

The dense layer is a fully connected neural networks. The weights, which represent the degree of connectivity between nodes, are adjusted to reduce the error as the training repeats.

The output layer receives the output value of the dense layer as an input value. "Softmax" was used for the output layer's activation function. The function presents the probability that the data entered in the model belong to a particular class. It gives a probability distribution whose total sum of the probabilities of belonging to each class is 1. Figure 4 shows the overall structure of the model and flow of data.

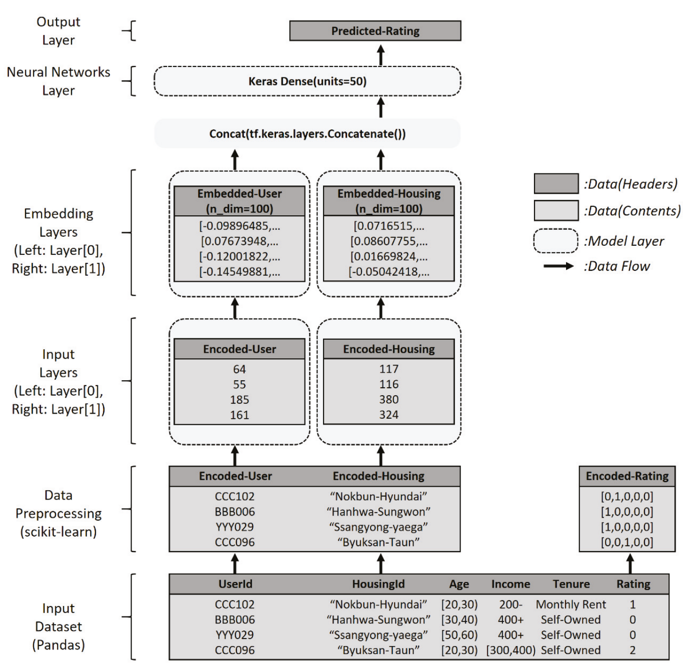

Figure 4. Model structure and the data flow.

5. "SeoulHouse2Vec" Model Training, Validating and Evaluation with Confusion Matrix

The recommendation system was trained and validated in supervised-learning method. In the initial phase of the training, embedding values are rather random and "trainable". However, after training proceeds and error decreases, the embedding values of the users and the profiles are rather "meaningful," which means their own vector values may reflect an atypical preference and intrinsic value of the given data. In this regard, if a specific user prefers a specific housing profile (item), the system recommends items that have close embedding distance to the user-liked item. From the user's viewpoint, it can be assumed that if two different users have close embedding distances, then their preferences for a given specific housing alternative may be similar.

Figure 5 shows the process of how supervised-learning classification problem can be cast to recommendation via using the concept of embedding. In the initial phase of the training, items are mapped to embedding layer in random order. Training process consists of forward and back propagation. In the forward propagation step, the mapped values are input to the dense layer, and the dense layer predicts the probability of belonging to a specific class. This prediction value calculates the difference with the label, which is the error. This error value is passed back to the embedding layer, and the model changes the mapping values of individual items in a way to reduce this error. This is referred to as backpropagation. After some iterations of this process, items are mapped in a way to reflect intrinsic, atypical, and abstract characteristics of the data in numeric values.

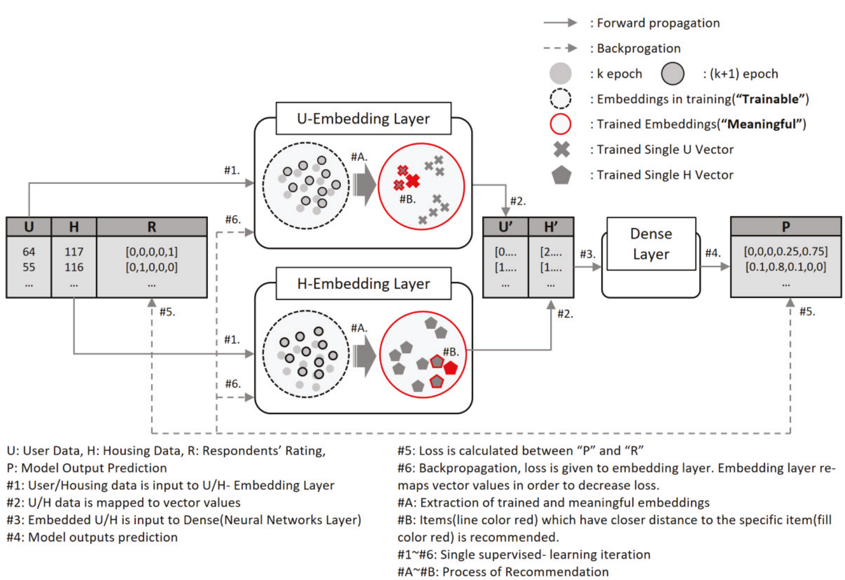

Figure 5. Relationship between the supervised-learning and embedding-based recommendation process.

5.1. Model Training and Validating for Tuning Model Hyperparameters

In this section, the model training and validating was conducted to set the embedding dimension and the unit of the dense layer.

In total, 6450 (215*30) data units were used in the process, namely the Rating values explicitly expressed by 215 respondents for 30 profiles. Using the "train_test_split" function in the scikit-learn API, from the entire data, 1293 were split as the evaluation data.

The embedding dimension consisted of a range from 2D to 200D, and the dense layer units from 5D to 300D. The model training and validating was conducted with a range of different combinations of the two hyperparameters. If both hyperparameters were set to values greater than the value of the range, overfitting occurred in which only training data were learned, limiting that range. The training iterations were set to 300. Among the various hyperparameters combinations, the highest accuracy was indicated when the embedding dimension and dense layer unit were (200, 50), respectively, and the second highest accuracy was (100, 50). Furthermore, (2, 10) had the lowest accuracy. This is shown in Figure 6a. The more the training was repeated, the errors decrease, as shown in Figure 6b.

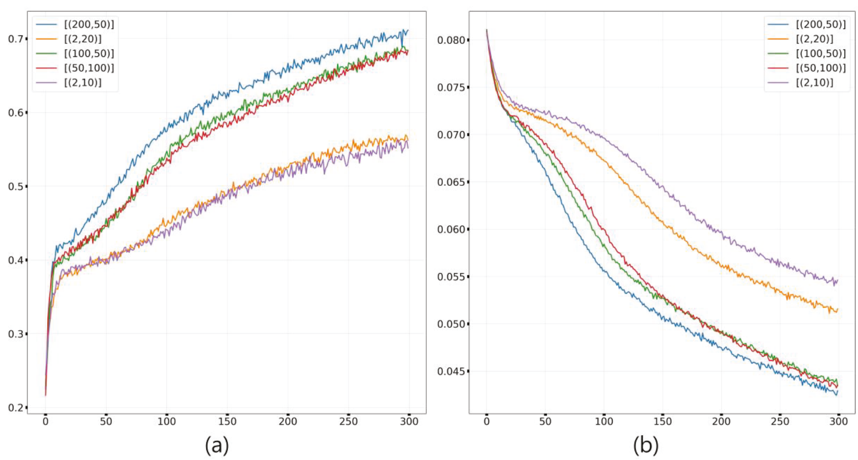

Figure 6. Model training: Accuracy and loss change over 300 epochs—(**a**) accuracy and (**b**) loss.

Figure 7 visualizes in two dimensions the changes in coordinates of individual items in the Housing Embedding Layer and User Embedding Layer as the number of training iterations was repeated. The "SeoulHouse2Vec" model is difficult to visualize because the individual users and housings are each mapped to the vector space. Therefore, the t-distributed stochastic neighbor embedding (t-SNE) method was used. The approach enables visualization by converting high-dimensional vectors that are difficult for users to intuitively understand into low-dimensional vectors while maintaining relative similarity and data characteristics between the individual items.

20 of the 679 and 215 items were randomly extracted, respectively. In (a), the 20 arbitrarily extracted housing profiles represented in relatively small circles are coordinate values when the training was repeated 100 times. The relatively large X-shaped housing profiles are coordinate values when the training was repeated 300 times. Based on housing profiles #88 and #625, the distance was closer when the training was repeated. In (b), the user represented in a relatively small circle is the coordinate value when the training was repeated 100 times, while the user represented in a relatively large pentagon is the coordinate value when the training was repeated 300 times.

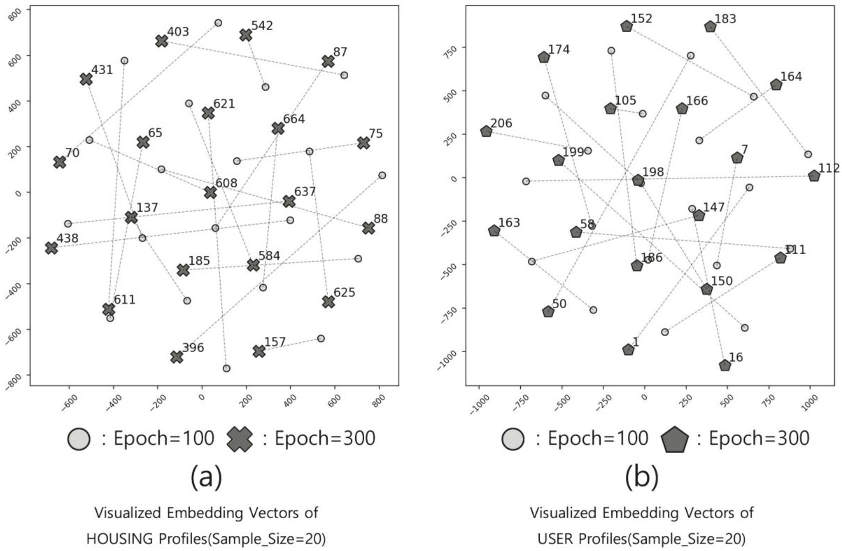

Figure 7. Change of vector values over the training epoch—(**a**) housing and (**b**) users.

5.2. Evaluation with Confusion Matrix for Estimating Final Performance of the Model.

The model was evaluated using three metrics: Precision, Recall, and f1_score for models (200, 50) and (100, 50), which demonstrated the highest accuracy during the previous model training and validating phase. For this, a confusion matrix was created. The confusion matrix, which is also referred to as the error matrix, is a common technique for evaluating and visualizing algorithm performance in machine and deep learning classification problems. Figure 8 shows a concept of the confusion matrix that can be created in a binary-classification problem. Precision is the ratio that the label, which is the actual classification of the data, is TRUE, from among the cases where the model's prediction for the input data is TRUE. Recall is the ratio the model's prediction is to TRUE from among the cases where the actual data classification is TRUE. The f1_score is the harmonic mean of precision and recall.

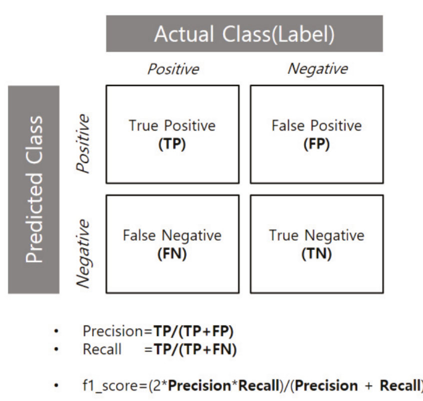

Figure 8. Concept of confusion matrix, precision, recall, and f1_score.

The trained model is a multi-classification model with five label values. The metrics can be measured based on a specific label class; here, the metrics were calculated based on the case of “Rating = 1” (least preferred), which comprised the largest share among the five classes. From the perspective of housing preference, the model maps the survey respondents and housing profiles to embedding vectors through the previous training process. In the evaluation process, arbitrary respondents and housing profiles are received as input values, and “Rating = 1” scores are not given to the model. If the model predicted that the respondent’s score for the housing profile is “Rating = 1” and the respondent’s actual score for the profile is “Rating = 1,” then this is considered a “True Positive.”

For model (100, 50), precision and recall were measured at 0.679 and 0.761, respectively, based on Rating = 1. The f1_score was measured at 0.718.

For model (200, 50), the precision and recall values were measured at 0.666 and 0.763, respectively, based on Rating = 1. The f1_score or harmonic mean was measured at 0.711.

Based on the three metrics, the (100, 50) model demonstrated slightly better performance in terms of confusion matrix. Figure 9 shows the confusion matrix of the two models: (a) (100, 50) and (b) (200, 50).

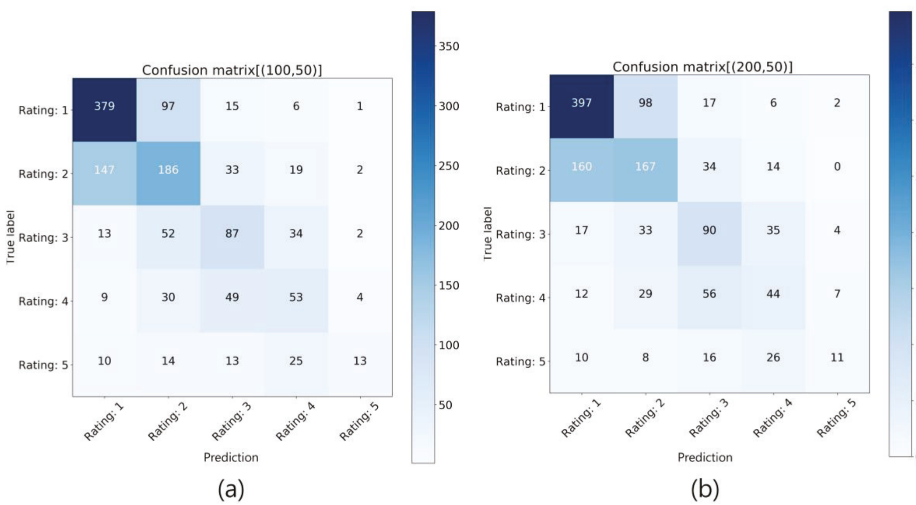

Figure 9. Model evaluation: Confusion matrix of models (**a**) (100, 50) and (**b**) (200, 50).

6. Scenario-Based Demonstration of “SeoulHouse2Vec” Model

This section provides one possible usage and application of the built model in terms of analyzing housing preference and supporting housing decision-making via recommendation of the profiles. Two research scenarios were suggested, respectively. In the previous survey step, since the demographic characteristics of the survey respondents were not evenly distributed and the size of the dataset is limited, the scope of interpretation and application of the research scenarios apply to only the 215 respondents and the 679 housing profiles. Future studies must investigate a broader scope of model application and results analysis. This study created two research scenarios, which are housing preference analysis and housing decision-making. In the scenario presentation step, a brief theoretical review was conducted to create the scenarios. In the model application step, acquired dataset and the built model was utilized. In the results interpretation step, the application results of the model were interpreted and visualized.

6.1. SeoulHouse2Vec Model Demonstration Scenario 1

6.1.1. Scenario: Multi-Attribute Utility Theory

A common method to quantitatively measure users' residential preferences is the multi-attribute utility theory (MAUT), which is a compositional model. After giving weights based on a scale of 0 (least important) to 100 (most important) to each attribute's level, the utility and preference between the alternatives were quantitatively evaluated by adding the value of each attribute and the product of the weighted value of each attribute value as assessed by the user. This technique has the possibility of identifying the relative importance between multiple attributes of a housing from the user's viewpoint and quantitatively measuring the preference [58–65].

Studies on residential preference using MAUT usually analyze the correlation between respondents' socio-demographic attributes and the weights of multiple residential attributes. They present housing alternatives that a group sharing particular socio-demographic attributes might prefer and quantitatively measure these preferences. However, these studies are limited in that they were unable to analyze individual units belonging to the group but showing different preferences.

Therefore, this study performed a survey using MAUT, which can identify the relative importance between multiple attributes, and sought to interpret the individual preference differences that show different preferences within the same group by analyzing the importance according to the housing variable of each individual unit.

To identify different preferences within the same group, a group was selected in which respondents shared specific socio-demographic attributes. The embedding distance between respondents was then measured to indicate the similarity of residential preferences within the group. Figure 10 shows the ranking of the embedding distances between eight individuals in a group with the same socio-demographic attributes: they were aged 50–60 years (age), earned KRW 4 million or more (monthly household income), and had "Jun-se" (housing tenure type). With the eight users in the group, 27 (48%) of the 56 rankings indicated different preferences with a ranking below 120. This indicated the need for a more personalized approach, since some cases belonged to a group that shared the same attributes but indicated different preferences for individuals.

	A001	A017	C048	Y001	Y016	Y027	Y031	Y004
A001	0	55	109	84	45	191	204	116
A017	18	0	29	97	50	6	67	54
C048	141	117	0	187	214	171	212	113
Y001	127	193	179	0	142	186	160	138
Y016	87	154	213	141	0	173	150	66
Y027	201	31	165	182	176	0	147	123
Y031	170	64	164	56	39	59	0	32
Y004	26	19	11	13	1	20	7	0

Highly Similar — Not Similar

Figure 10. Embedding ranking of users with identical socio-demographic attributes.

Thus, the study aimed to conduct the analysis using the SeoulHouse2Vec model, in which the minimum unit of analysis is the individual's preference. Based on users who share socio-demographic attributes but show different preferences, or users who do not share any socio-demographic attributes but have the same preferences, the study aimed to present and implement a scenario for analyzing residential preferences with the MAUT method.

6.1.2. SeoulHouse2Vec Application with MAUT

Randomly selected respondents were asked about the relative weight of the residential preference variables in the MAUT survey. The six housing preference variables presented to respondents were accessibility to the subway, accessibility to the supermarket, accessibility to educational facilities, residential facilities, accessibility to parks, and investment value. For each housing preference variable, the respondent answered on a scale ranging from 0 (least important) to 100 (most important). The interior factors of the dwelling are the area of the unit, price per *pyeong*, number of rooms, and number of bathrooms, which may not show a linear preference. They were grouped as house interior factors and their importance was indicated. Each of the four items was divided into three levels. Area of house was delineated as small (80 m^2 or less), medium (80–109 m^2), and large (109 m^2). Price per *pyeong* was divided into KRW 10 million or below, KRW 10 to 15 million, and KRW 15 million or more. Number of rooms was delineated as two or less, three, and four or more, and number of bathrooms as one and two or more. The score for each was then assessed. The house interior factors were combined in the assessment because individuals' nonlinear preference was evident. For example, in the case of the importance score for time to metro, which showed a linear preference, less time means higher utility. However, for area of housing, which has a nonlinear preference, a larger size does not mean higher utility. The preferred size of homes may vary by respondent because they may prefer smaller houses considering the maintenance costs or larger houses because of the size of the family.

Of the survey respondents, randomly selected "USER_A001" was aged 50 to 60 years (age), earned KRW 4 million or more (monthly household income), and was leasing (housing tenure type). In addition, the importance values (weights) of the user's residential preference variables were as follows: accessibility to the subway (80), accessibility to the supermarket (50), accessibility to educational facilities (20), house interior factors (80), accessibility to parks (60), and investment value (20).

First, of the users who share all the socio-demographic attributes of USER_A001, "USER_Y031" is the 152nd furthest away from USER_A001. Comparing the importance of the residential preference variable of the reference respondent and USER_Y031, accessibility to the subway is similar: 80 for the reference respondent and 90 for the comparison respondent, below the difference range of 10. However, the weights for the other five categories assigned by the comparison respondent were accessibility to the supermarket (30), accessibility to educational facilities (60), house interior factors (20), accessibility to parks (40), and investment value (20). Being above the margin of error of 10 or more, the two respondents' preferences for most categories were non-similar. Therefore, even in groups with matching demographic characteristics, residential preferences may vary depending on the difference in importance each respondent assigns to each variable. These different preferences were expressed over relatively distant embedding distances. This is shown in Figure 11.

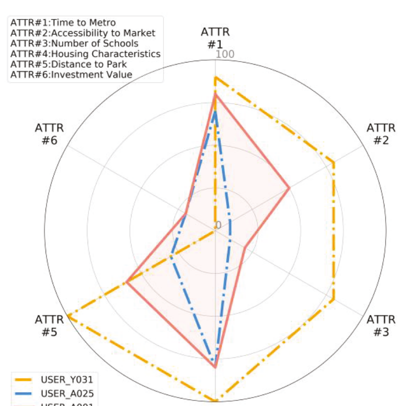

Figure 11. Spider diagram for comparing relative importance of the housing attributes among the users.

6.2. SeoulHouse2Vec Model Demonstration Scenario 2

6.2.1. Scenario Presentation

According to the Population and Housing Survey conducted by Statistics Korea in 2017, 19% of Korea's total population resides in Seoul, which counts about 9,700,000 ([1,2]). Based on the population movement in Seoul in 2019, of the about 1,400,000 people that moved in. In addition, of the 1,400,000 people that moved out [66]. This shows that population movement and housing market in Seoul are relatively active. This study presents and implements a scenario in which a family searches for the housing throughout Seoul, with a high preference for the apartment "HanhwaGgumAeGreen" located in Jayang-dong, Gwangjin-gu, a district of Seoul. By doing so, the study visually presents specific utilization measures of the model and its results.

6.2.2. Model Application

Through the model's training process, the profiles were mapped to the embedding layer. The distances of the mapped profiles were calculated based on the preferred profile(target). If a particular user prefers the profile, the recommendation system will work in a way that sequentially presents some profiles close to the profile.

The dataset for the demonstration consisted of the embedding distances from the target apartment to the other apartments, names of the apartments, latitude, and longitude. This dataset was visually represented on the map of Seoul using Tableau, a data visualization program. Individual profiles are represented in a marker style circle with a black border on the map. A closer embedding distance from the preferred apartment was represented in red, and a farther distance in green. "HanhwaGgumAeGreen", the reference for the calculation, was expressed in blue "X" characters on the map. This is presented in Figure 12: (a) shows a geographical range based on the entire Seoul area, and (b) is based on the Gwangjin-gu area where the apartment is located.

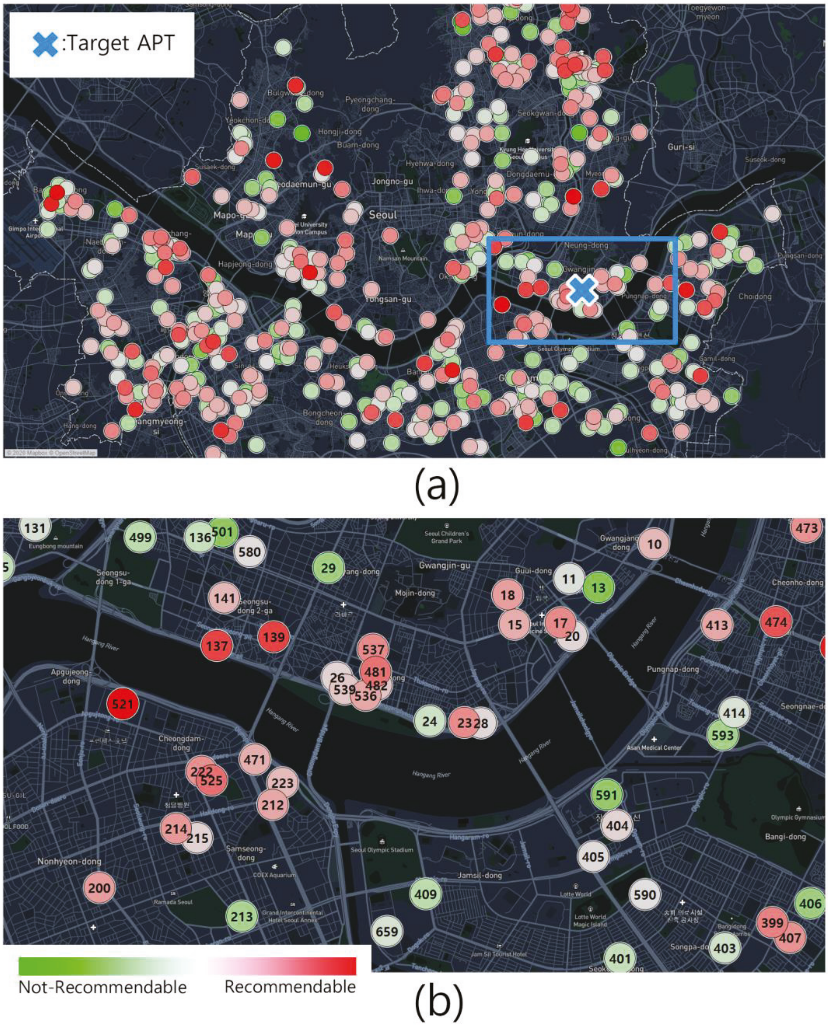

Figure 12. Geographic visualization of the housing profiles based on the embedding distance: (**a**) geographical range: Seoul, (**b**) geographical range: Gwangjin-gu.

6.2.3. Data Analysis

Table 3 shows the values of the nine attributes for the entire profiles and the preferred apartment: time to metro (ATTR#1), accessibility to market (ATTR#2), number of schools (ATTR#3), housing area (ATTR#5), number of rooms (ATTR#6), number of bathrooms (ATTR#7), distance to park (ATTR#8) and investment value (ATTR#9).

The table also shows the average value corresponding to the attributes of the top 50, top 25, top 10, and top 5 apartments with a close embedding distance from the preferred apartment. First, for ATTR#1, time to metro, a smaller value means better accessibility. The average of the 679 profiles is about 11.23 minutes and 7 minutes for the reference. We see that a closer embedding distance starting from the Top 50 to the Top 25, 10, and 5 apartments means better accessibility to the subway station. For ATTR#2, a higher value indicates less accessibility. Interesting is that a higher value here means lower worth. Closer distance from the preferred profile shows an increasing value. Both ATTR#1 and ATTR#2 are related to accessibility. While a closer embedding distance improves the accessibility of ATTR#1, that for ATTR#2 decreases. This suggests that if this apartment is preferred, access to the subway station rather than to the supermarket will play a more important role in forming the preference. This may be interpreted as a trade-off between the two attributes.

For ATTR#5, housing area, the reference apartment has an area value higher (larger area) than the average of the overall profile. The top 50 has a higher value than the top 25 and top 10; thus, it is not possible to identify trends. However, the top 5 housing profiles with the nearest embedded distance have a relatively high value of 96.96. For ATTR#7, the number of bathrooms, the top 50, 25, 10, and 5 all have values higher than the average of the entire Seoul area, but no change in attribute values were found based on the difference in the distance.

Regarding ATTR#3, the reference apartment was preferred, despite its value of 6 for the number of elementary, middle, and high schools within 1 km, which is less than the average 7.79 of the entire profiles. This suggests that ATTR#3 had a relatively low weight in survey respondents' preferences. For ATTR#6, the number of rooms, the top 5 had a higher value than the overall average in Seoul, but no difference was confirmed based on the embedding distance. ATTR#8 is the distance to the nearest park. The reference apartment had a lower value (closer to the parks) than the entire Seoul area, but no relationship was found between changes in the embedding distance and the value.

Table 4 shows top 5 housing profiles which have close embedding distance to the reference.

In sum, in the demonstration, the preference for the reference apartment may be linked to other apartments that are close to the subway station, have a large area, have a large number of bathrooms, and are worth investing in.

Table 3. Comparison of the housing attributes based on the embedding distance to the reference: Top 50, top 25, top 10, and top 5 closest.

	ATTR#1	ATTR#2	ATTR#3	ATTR#5	ATTR#6	ATTR#7	ATTR#8	ATTR#9
Total	11.23	1870.40	7.79	83.87	3.09	1.71	233.28	0.42
Reference	7	1600	6	138.85	4	2	100	0
Top 50	12.72	1876.06	7.6	87.78	3.18	1.8	262.78	0.48
Top 25	12.12	1949.32	6.68	84.87	3.08	1.84	256.28	0.44
Top 10	11.50	2137.8	7.1	85.24	3	1.8	254.9	0.7
Top 5	5.4	2680	8.6	96.96	3.2	1.8	258.2	0.6

ATTR#1: time to metro, **ATTR#2:** accessibility to market, **ATTR#3** number of schools, **ATTR#4:** housing price, **ATTR#5:** housing area, **ATTR#6:** number of rooms, **ATTR#7:** number of bathrooms, **ATTR#8:** distance to park, **ATTR#9:** investment value.

Table 4. Top 5 recommendable housing profiles.

Distance(Closest)	Profile (*Gu*, *Dong*, and Apartment Name)
1st	Dongdaemun-gu, Jangan-dong, Raemian Jangan 2-Cha
2nd	Gangnam-gu, Apgujeong-dong, Hanyang 3
3rd	Gangseo-gu, Banghwa-dong, Banghwa 3-Danji
4th	Mapo-gu, Yonggang-dong, Mapo Yongang Samsung Raemian
5th	Gangdong-gu, Cheonho-dong, Raemian Gangdong Palace

7. Conclusions

To build SeoulHouse2Vec, an embedding-based recommendation system, a demonstration was conducted by creating housing profiles, conducting preference surveys, constructing, validating and evaluating a model, and presenting two scenarios. The significance and contributions of the study are highlighted below.

- Sustainability in architecture, previous research focused on the use of energy-efficient materials, designing high performance building envelop and optimizing HVAC operation, etc. Unlike previous research, this study is meaningful in that it investigates the rational use of limited housing-related goods. Given that the consumption and supply of housing utilizes limited land and spatial resources, both consumption and supply are closely related to sustainability, which has long-term personal, social, and environmental impacts. Moreover, it may not be possible to revise or reverse the decision. This study suggested the feasibility of using a recommender system to support rational decision making in both housing consumption and supply.

- Even with the fact that housing supply ratio in Seoul is about 95%, housing prices are rapidly increasing as of late. To address this in terms of massive housing supply, policymakers are discussing the lifting of the greenbelt zones where development has been restricted over the years. While there are various causes of steep rises in the prices, the model proposed in this study has one potential technique to solve problems known to prevent the housing market from functioning rationally, including imbalanced information between housing consumers and suppliers, rather hasty housing decision based on consumers' biased information, and the limited exploration of the alternatives.
- From the user's viewpoint, the scope of existing housing alternative searches was limited to the local scope of *dong* or *gu* (district). However, the SeoulHouse2Vec model proposed in this study is significant in that it extends the search scope for housing alternatives from the previous *dong* to the entire Seoul area by utilizing public big data and GIS data.
- If Seoul's regional scope is expanded through data mining and web crawler technology to collect alternatives throughout Gyeonggi-do and South Korea, it will be possible to apply a further expanded model.
- The SeoulHouse2Vec model provides one possibility of assessing the outcome of past housing decision-making. If the level of housing satisfaction is higher than the current one, certain alternative with the attributes similar to the current one can be presented. Conversely, if the current housing satisfaction level is low, an alternative with the opposite attributes, one whose embedding distance is far, may be prioritized. This will help support the current housing decision-making process by quantitatively analyzing and reflecting the past decision-making process. This may be particularly useful for users who have little experience and knowledge in searching for housing alternatives.
- SeoulHouse2Vec has the potential to track the user's decision-making process, analyze preferences, and support the architect's planning and initial design stage. It is now becoming increasingly important to reflect users' perspective in architectural planning and design. This is an important factor not only in design quality, but also in determining the market price of buildings. Currently, the architectural planning phase involves analyzing the requirements of prospective users and contractors, and relying on the architect's knowledge, experience, and intuition to generate the information necessary to proceed with the design process. The model proposed here includes user information on age, income, and housing tenure type; housing profile information related to housing attributes; and preference information, which is the relationship between the user and the alternatives. The dataset may provide a quantitative basis in the architectural decision-making process.
- The SeoulHouse2Vec model not only measures users' housing preferences based on demographic attributes, but users with divergent demographic characteristics may also have highly similar housing preferences depending on the importance of each preference variable. Even in groups with matching demographic characteristics, housing choice may vary depending on how significant respondents consider each variable. This preference tendency can be reflected through the embedding method.

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sustainability

Review

A Review of Smart Design Based on Interactive Experience in Building Systems

Zhen Li [1], Jiao Zhang [1], Mengwan Li [1], Jizhuo Huang [2,*] and Xiangyu Wang [2,3]

1 School of Management, Jiangsu University, Zhenjiang 212013, China; janeli@ujs.edu.cn (Z.L.); 2221810022@stmail.ujs.edu.cn (J.Z.); 2221810038@stmail.ujs.edu.cn (M.L.)
2 College of Civil Engineering, Fuzhou University, Fuzhou 350108, China; Xiangyu.Wang@curtin.edu.au
3 Australasian Joint Research Centre for Building Information Modelling, School of Built Environment, Curtin University, Perth, WA 6845, Australia
* Correspondence: jzhuang@fzu.edu.cn

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Abstract: Smart building is the result of the penetration of information technology and control technology into traditional buildings, and is the future development direction of buildings. User-centric building smart design can achieve a sustainable life, and smart technology integration based on smart design can support sustainable development and improve user satisfaction, happiness, and overall quality of life. In intelligent design, researchers focus on the "people-oriented" approach, designed to bring users the ultimate interactive experience. Based on the interactive experience principle of smart design in the smart building system, this article classifies and summarizes intelligent design from the "five senses" interaction, including visual interaction, voice interaction, tactile interaction, cognitive interaction, and emotional interaction. We analyze the application of smart design in architecture and discuss how to embody the principles of user-centered interactive experience design in the process of smart design. This article provides a comprehensive and systematic literature review, clarifies the importance of the "people-oriented" approach in the smart design of buildings, and summarizes how to improve the sustainability of intelligent buildings from the perspective of a "people-oriented" approach. This paper proposes future research suggestions and directions and promotes the sustainable development of the smart building.

Keywords: smart building; interactive experience; "five senses" interaction; people-oriented

1. Introduction

Since the 1990s, digital technology has developed rapidly and penetrated into various fields, and the application and service based on computer systems have proliferated. With the continuous expansion of the Internet to ordinary family life, a powerful and highly smart building system is gradually formed, making it possible to achieve a safer, more convenient, energy-saving, and intelligent home life. Smart building is the result of the penetration of information technology and control technology into traditional buildings [1–3]. From the first summit in 2000 to the 19th China International Building Intelligence Summit, although the road to intelligent building automation in China has undergone many twists and turns, this process has been unstoppable. The development of science and technology has made people unswervingly pursue a higher quality of life. Smart buildings have attracted more and more attention as representatives of high-quality information life. For example, Fuji Xerox Parker's main research and development areas are smart workplaces (spaces) and flexible working methods. The main achievements include a wearable remote video communication system and a desktop file management and remote communication system, aiming to make information transmission more efficient, more accurate, more interactive, and social. The Computer and Artificial Intelligence Laboratory of the Massachusetts Institute of Technology is one of the world-renowned computational science and artificial intelligence laboratories. It is also actively studying the application of artificial intelligence technology in urban buildings, looking for innovative ways to make systems and equipment safer, more convenient, and more effective to benefit humankind.

Buildings are for the realization of people's hope and demand. As an information exchange platform between a smart system and users, the intelligent design of intelligent building systems plays an important role. User-centric building smart design can achieve a sustainable life, and smart technology integration based on smart design can support sustainable development and improve user satisfaction, happiness, and overall quality of life [4]. In intelligent design, researchers focus on the "people-oriented" approach, designed to bring users the ultimate interactive experience. The human–computer interaction design has attracted more and more attention. Interaction design is to create and support human behavior design through physical, virtual, or service products, focusing on defining the interface related to the behavior of human creation [5]. Human–computer interaction is to constantly enrich the user experience of the rich, to achieve the purpose of optimizing the interaction experience, and to build a more practical, easy-to-use, and humanized smart building system. Therefore, the interaction experience plays an important role in the smart design stage of the smart building system. Based on the rapid development of smart buildings, many smart building technologies have emerged one after another. In addition to some physical designs, such as sensors and actuators, there is a growing demand for interactive experience design about emotional perception. For example, Europe, the United States, and Japan have adopted a series of interactive experience-related technologies for population aging, and have been well promoted [6].

In the design of smart building systems, different smart technologies should adopt different interaction modes for different users, and smart designers should pay attention to different user characteristics, that is, the principle of a "people-oriented" approach. According to the survey of the beneficiaries of smart buildings, and according to the age division principle, users can be divided into three stages, mainly including children, adults, and the elderly. In the current social background of China, the demand for human–computer interaction smart design of smart buildings for these three types of users is also increasing. First of all, in terms of children's interactive experience needs, and in the process of children's growth, the family is the first stop and plays an important role. Parents' educational concept and family environment will directly affect children's development. Therefore, the market demand of human–computer interactive smart building teaching systems related to children's early education and preschool education is increasing gradually. Secondly, in the aspect of adults' interactive experience demand, with the continuous improvement of Internet information, there are home office, remote conference, and other smart building systems, and users put forward higher requirements for the life style of interactive experience in smart buildings. Finally, in terms of the interactive experience needs of the elderly, the trend is of the aging population and the social status quo of rapid development of science and technology [7]. The physical and mental health of the elderly is valued, and the demand for intelligent assistance in the daily home life of the elderly continues to expand. On the other hand, it makes a large number of intelligent building auxiliary equipment emerge. To a certain extent, home auxiliary equipment can improve the health and life ability of the elderly, so the interactive smart building equipment for the elderly is an opportunity for the development of smart home systems. User-centered intelligent design can better promote the sustainable development of smart buildings. Sustainability here no longer refers to resource conservation and the green environment, but to bringing users a sustainable life.

The user-centered interactive experience design principles play an important role in the intelligent design of smart buildings. However, most review articles for smart buildings mainly focus on the development of key technologies or intelligent technologies. Few studies start from the perspective of interactive experience and use the "five senses" interaction type to prove the importance of the "people-oriented" approach in smart design. As the carrier of smart buildings and users, the senses will affect the user experience of smart building design. The five senses are interrelated and inseparable, and the mutual influence of each perception element constitutes the entire experience of architectural perception. Starting from the perspective of the "five senses" can better reflect the "people-oriented" principle, and provide more possibilities for smart building design, thereby improving the comfort, satisfaction, and sustainability of smart buildings. Therefore, based on the interactive experience principle of smart design in the smart building system, this article classifies and summarizes intelligent design from the "five senses" interaction, including the visual interaction, the voice interaction, the tactile interaction, the cognitive interaction, and the emotional interaction. We analyze the application of smart design in buildings and discuss how to embody the principles of user-centered interactive experience design in the process of smart design. This article provides a comprehensive and systematic literature review, clarifies the importance of the "people-oriented" principle in the smart design of buildings, and summarizes how to improve the sustainability of intelligent buildings from the perspective of a "people-oriented" approach. This paper proposes future research suggestions and directions and promotes the sustainable development of the smart building.

2. Method

This research used a content analysis method for review analysis. The content analysis method can be used to systematically and effectively make inferences based on the collected data, so as to conduct qualitative and quantitative analysis of the research status, which is beneficial to describe the overall application of the "people-oriented" interactive experience principle in smart design [8]. The qualitative analysis of the content analysis method can reflect the main characteristics of the literature; the quantitative analysis of the content analysis can objectively summarize the research content, and reveal and summarize the potential information of the existing literature in terms of time, region, and so on. Therefore, the content analysis method can more comprehensively analyze the application of the "people-oriented" interactive experience in smart design, and ensure that the research results are reliable and effective. During the review process, the work design of the review study was particularly borrowed from the framework of Kim [9].

2.1. Step 1: Identifying the Research Question

The daily smart building system is mainly composed of people, control systems, and electronic products, as shown in Figure 1. Among them, the control system establishes an intelligent connection between people and electronic products for mutual information transmission and feedback. On the one hand, the performance of the control system determines the intelligence of the building system. On the other hand, people belong to the main service objects of the smart building system, and the performance of the control system also determines the satisfaction degree of the people in the smart building service. The performance of the control system mainly depends on intelligent technology. The "people-oriented" interactive experience design principle based on cognitive psychology, design psychology, and other related theories has a significant impact on the design of smart building technology, fully plays the role of interactive experience, builds a bridge between information transmission and the intelligent environment, and achieves a more complete human–computer interaction mode.

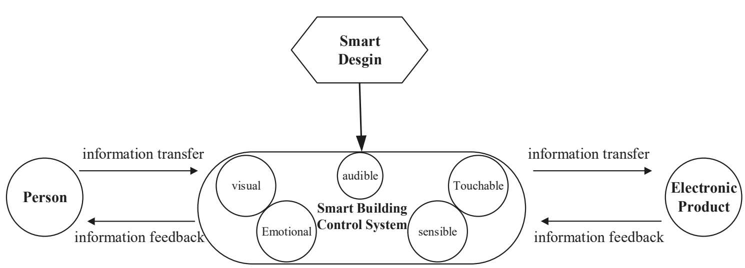

Figure 1. Basic model diagram of a smart building system.

Therefore, this article first consults the existing reviews of the smart design in buildings, clarifies which aspects are currently involved in those reviews, or does not cover too much, confirms the frequency or degree of attention of the interactive experience in those reviews, and ensures the research significance of the interactive experience in this article on the review of smart design in buildings. This article starts with the interactive experience principles of smart design in smart buildings, and follows the "five senses" interactions involved in interactive experiences, including visual interaction, voice interaction, tactile interaction, cognitive interaction, and emotional interaction. It classifies and summarizes smart design, analyzes the application of intelligent design, especially the interaction characteristics of the intelligent environment and the users, and explores how to embody the "people-oriented" interactive experience design principles when designing a smart environment.

2.2. Step 2: Collecting Studies

This article used the search terms related to "smart design" and "interactive experience" to conduct a literature search on the five major databases of ISI Web of Science, Science Direct, Ei Village, ACM Library, Scopus, and IEEE Explore. These search terms are universally accepted from journal to journal and from continent to continent, and there is no regional and journal bias. Wearable mobile devices and smart operating platforms are the mainstays in the smart building; for the "five senses" interactive experience, we searched for visual interaction, voice interaction, tactile interaction, cognitive interaction, and emotional interaction. Finally, all the collected documents were reviewed, and preliminary screening was conducted.

2.3. Step 3: Screening Literature

In order to ensure that the collected documents were consistent with the definition of the scope set in this article, all the collected documents have undergone strict screening and review, and the inclusion and exclusion criteria have been formulated as follows: The inclusion criteria were (1) literature that clearly introduces smart building equipment or technology; (2) the article aims to demonstrate the application of "people-oriented" interactive experience design principles in smart buildings; (3) the article is published after 2010; The exclusion criteria were (1) survey-type research using a scale or questionnaire; (2) comprehensive research on smart building panel design based on interactive experience; (3) exploring the developmental potential of interactive experience in smart building devices or usability studies. After determining the inclusion and exclusion criteria, the title was first screened, followed by the abstract, and finally the full-text review.

2.4. Step 4: Analyzing Literature

We conducted a qualitative and quantitative analysis of the filtered literature. Among them, qualitative analysis was used to identify the year and region of the literature, analyze the interactive characteristics of the intelligent environment formed by intelligent design and users, and explore how to embody the "people-oriented" approach in the process of intelligent design. Quantitative analysis was used to determine the number of years and geographical distribution of the literature. Through the above analysis, we can ensure the development of a trend of application of interactive experience in intelligent design, and propose better future development directions and suggestions.

In addition, the Figure 2 shows more details of the review process of this article.

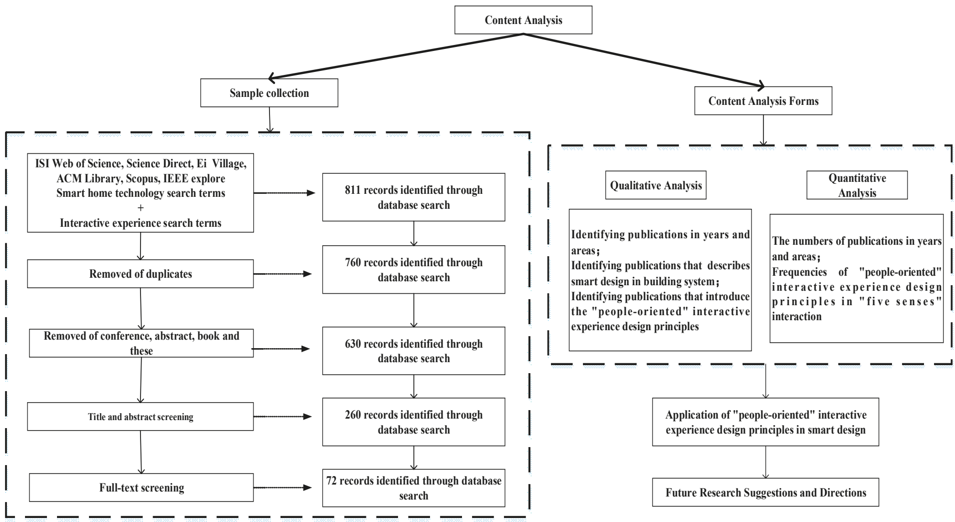

Figure 2. Content analysis procedure.

3. A Survey of Research on Smart Design Based on Interactive Experience

3.1. Trends

3.1.1. Publications in Years

Figure 3 shows the trend of the final selected literature over time. The average number of published studies in 2010–2020 is about 7.2, among which the most published articles in 2018 are 18, far exceeding the average. Figure 3 also shows us clearly that the number of articles published before 2014 is far less than six, but after 2015, the number has increased significantly, which means that people pay more and more attention to the importance of the "people-oriented" interactive experience design principle in the application of smart building systems.

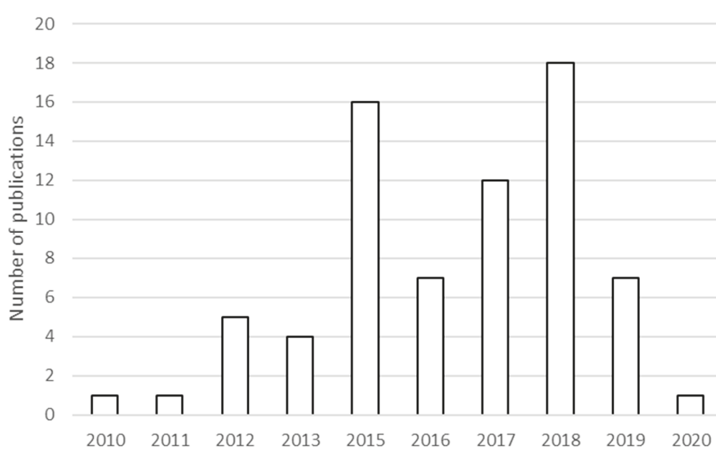

Figure 3. Publication trend in years.

3.1.2. Applications in Geographical Areas

Table 1 shows the literature distribution of "people-oriented" interactive experience design principles applied in smart building systems in various countries and regions. Because many studies involve authors from many countries, the principle of our classification was based on the geographical location of research data or the research background in each research. This method can better reflect the geographical distribution of interactive experience in the application of smart design in building systems. According to the data in the table, there are 13 articles in China, accounting for 19.11%, followed by 8 in the United States, 4 in France, 3 in India, 3 in Australia, 3 in Spain, and 3 in Romania.

Table 1. Distribution by countries or regions.

Country or Region	Number of Publications	Percentage of Publication (%)
China	15	19.40
United States	9	10.45
France	4	5.97
India	3	4.48
Australia	3	4.48
Spain	3	4.48
Romania	3	4.48
Italy	2	2.97
Japan	2	2.97
Netherlands	2	2.97
Greece	2	2.97
Portugal	2	2.97
Taiwan	2	2.97
Canada	2	2.97
Sweden, Finland, Singapore, Arabia, Earl, Malaysia, Mexico, Algeria, Israel, Pakistan, South Korea, Norway, Switzerland, Germany, Brazil, Serbia, Sri Lanka	2	1.49
Total	72	100

3.1.3. Application Fields

Table 2 shows the frequency of five different interaction modes in the literature, among which voice interaction is the highest (30.88%), followed by visual interaction and emotional interaction (20.59%), cognitive interaction (19.12%), and somatosensory interaction (14.70%). It was clearly found that the "people-oriented" interaction experience design principle has different degrees of application in different interaction modes, but these five interaction modes are indispensable in the smart building systems.

Table 2. Application frequency of different advanced experiences.

Interaction Type	Quantity	Percentage (%)
visual interaction	15	20.59
voice interaction	22	30.88
tactile interaction	10	14.70
cognitive interaction	14	19.12
emotional interaction	15	20.59

3.2. Review Results

3.2.1. The Visual Interaction

In the building design system based on visual interaction, (1) when constructing the intelligent environment, in order to realize the technical development on different platforms and different controls, the hardware of the intelligent building system will adopt different methods. For example, the 3D image synthesis method is introduced to apply the 3D display to the control interface of the intelligent building system, so as to enhance the authenticity, user friendliness, and visual comfort of the interface and enhance user interaction experience [10,11]. (2) In order to ensure the user-centered principle, users participate in building applications that can be configured and managed on the iOS platform, and evaluate their availability [12]. (3) Based on the characteristics of user vision, measures such as "staring" should be taken to attract users' visual attention, so as to achieve efficient communication between human and machine and improve user satisfaction [13,14]. (4) Based on the feedback mechanism of users, the conscious optimization model of the visual interaction system is established to support better human–computer interaction [15,16]. (5) Give full consideration to the needs of users, especially for users with special needs, such as the disabled, through remote consultation of the visual system; intelligent nursing data can be provided, and the technology that can control the home building system through eye movement is proposed to give full play to the visual interaction of users [17–19]. In the design stage of the intelligent building system, let users really participate in the work of intelligent technology design, collect user experience and user data, and establish a user information database, which can not only improve the visual level of the intelligent building system, but also improves users' comfort and satisfaction [20–24].

3.2.2. The Voice Interaction

Voice interaction enables the user to control the intelligent building system by voice so as to realize the automation and robustness of the intelligent building system [25–27]. In the process of intelligent design of buildings, researchers often take suggestions of user participation and use deep learning and other techniques to continuously optimize the sensitivity of speech recognition [28,29]. (1) Researchers pay attention to the voice characteristics of users, develop an inclusive multi-functional intelligent building voice recognition system, improve the accuracy of user voice recognition, and bring more functions and experiences to users [30–32]. (2) The elderly or users with speech defects may encounter a series of problems in the home environment. The special speech recognition system developed can help them solve speech disorders and ensure their safety and health in life [33–37]. (3) In order to satisfy the users in the long distance voice interaction under special environment requirements, the designers of the analysis of the intelligent building system in the process of long distance voice interaction in which may exist problems, put forward the speech recognition system for long distances, and broke the voice interaction possible distance limit, to improve the user experience in the intelligence environment [38–44].

3.2.3. The Tactile Interaction

Body sense interaction is mainly to use smart building system equipment to intelligently identify the user's actions or make physical contact with the user to realize human–computer interaction [45,46]. When gesture recognition becomes the main interaction mode in smart building systems, designers pay more attention to the optimization of gesture recognition technology. By examining the different needs of users in different stages, gesture recognition technology changes from ordinary static recognition to dynamic recognition, from a single gesture to multiple semantics, constantly enriching the participation and satisfaction of users in the smart building experience [47–49]. At the same time, in view of the needs of special users, especially for blind or visually impaired users, from the user's perspective, the tactile channel is used instead of the perception channel to avoid the frustration brought by visual defects.

The user-centered development of such a guidance model can effectively realize human–computer interaction and improve the user's satisfaction [50,51].

3.2.4. The Cognitive Interaction

Based on the different cognitive characteristics of users, in order to give full play to the advantages of cognitive interaction in smart building systems, a series of systems and devices are developed to meet the needs of users [52–55]. The interaction interface between the user and the smart building has a high impact on the user's experience. Analyze the cognitive characteristics of different types of users, and design the interaction interface from the perspective of information cognition, so as to reduce the cognitive friction generated by the user in the process of using a smart home, and then improve the user's use experience [56–59]. For the inevitable cognitive obstacles, especially with the coming of the aging age, there are many problems related to the decline of cognitive function. In order to supplement the cognitive function of the elderly users, the smart building user interface simulation model is established by the elderly users. Through the participation and feedback of the elderly users, the auxiliary system is proposed to realize the harmonious communication of the elderly in the intelligent environment and improve the performance of human–computer interaction in the intelligent environment [60–65].

3.2.5. Emotional Interaction

With the continuous improvement of users' needs, higher requirements are put forward for the building environment to obtain psychological and emotional satisfaction. In recent years, more and more emotional management systems based on emotional interaction have emerged in the smart building environment [66–68]. By analyzing the different emotional needs of different users, including emotional acquisition, emotional recognition, and all stages of emotional interaction, a highly interactive and experiential personalized and emotional intelligent device has been established [69–73]. The focus on the elderly user group is still the focus of emotional interaction. Design various emotional perception frameworks and devices to trigger emotional communication between the elderly and the smart building environment, and give full play to the importance of a "people-centered" approach [74–76].

3.2.6. Interactive Combination

The human–computer interaction in smart building is not only the use of a single interaction, but also the combination of different interactions in recent years. Through various combination modes, it can more comprehensively meet the user's requirements for interaction [77–80]. When integrating multiple interaction modes, users play a more important role in the smart design of the building system, especially for users with physical defects, and according to the real needs of users, through the combination mode of voice interaction and touchable sense interaction, the operation of the home system can be realized to ensure that such users complete their daily activities in the smart building system [1,81–83]. Many kinds of interactive combinations are more and more popular, which is an opportunity for the future development of smart building; of course, the difficulty of technology is also a challenge.

4. Conclusions

This paper starts with the principle of interactive experience of smart design in the building system according to the "five senses" interaction involved in the interaction experience, including visual interaction, voice interaction, tactile interaction, cognitive interaction, and emotional interaction. This paper classifies and summarizes smart design, and analyzes the application of smart design, especially the interactive characteristics between the intelligent environment and users. It also explores how to embody the principle of "people-oriented" interactive experience design when designing an intelligent environment, and finds the key position of users in the smart design of the building, as shown in Figure 4; that is, the importance of the "people-oriented" principle. From the perspective of a "people-oriented" approach, this paper summarizes how to improve the acceptance of intelligent buildings and promote the development of a sustainable life.

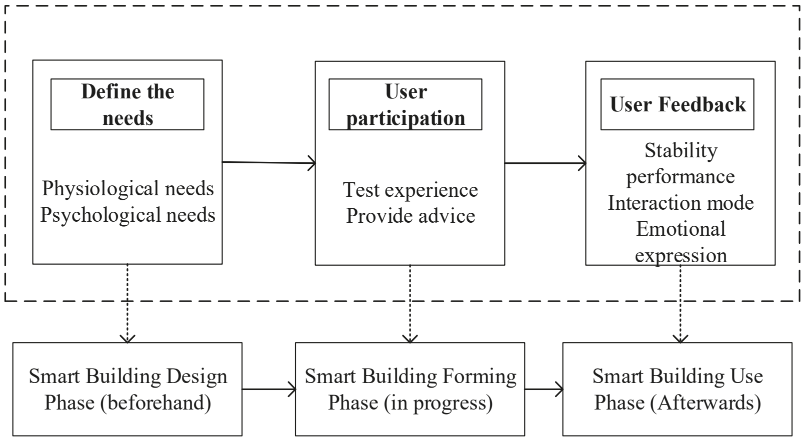

Figure 4. Application of interactive experience in smart design of the building system.

First, the principle of "people-oriented" interactive experience design is to ensure the security, effectiveness, and sustainability of the smart building system, including intelligent communication in the building environment, which fundamentally changes the traditional smart building interaction mode. By reviewing the smart design based on the principle of "people-oriented" interactive experience design, focusing on changing the problems that need attention of the principles of "people-oriented" interactive experience design and the process of "people-oriented" interactive experience application in the process of specific technology use, we can find that: (1) In the research of principles of "people-oriented" interactive experience, with the continuous development of the times, more and more attention has been paid. Especially after 2014, most of the research is in the context of China, and the development trend of the smart building system is to maximize the needs of all users. For example, when we measure a smart building system, the different effects of interaction may make different users feel differently about the same product. Therefore, we should pay attention to the key position of "users" in smart building design. User-centered product design can provide specific uses for specific users in specific use environments, ensure the effectiveness, user satisfaction, and other performance of smart buildings, and can adapt to more use environments and achieve sustainable living. When using the user-centered concept of the "people-oriented" approach to participate in interactive design, we need to pay attention to the following issues. The first are requirements. From functional requirements to emotional needs, methods such as user surveys are adopted to collect user data accurately to clarify the real needs of users [11,34,47]. The second is user participation. In each test process before product technology shaping, users should participate in the experience, express their true feelings, and put forward opinions. Then, special technical designers should retain operational opinions, constantly optimize product technology, and improve the satisfaction of the interactive experience of smart buildings [9,45,64]. (2) In the analysis of the existing research, it was found that not only single interactive applications, but also the combination of two or several kinds of interaction existed, aiming at providing users with a comfortable and satisfactory home experience [73–76]. In recent years, the frequency of the smart building system model or technology development of this combination model has gradually increased. It is obvious that technology is developing towards a more complex, intelligent, and humanized direction.

Second, in order to ensure the sustainable life brought by smart buildings, the principle of the "people-oriented" interactive experience of smart design in building applications will follow the following principles. The first is to see the demand clearly [24,39]. Before the development of smart home technology, the needs of users, including physiological needs (functional needs) and psychological needs (emotional needs), will be fully considered. In terms of physiological needs, the smart design of the building system has improved people's quality of life to a certain extent, bringing convenience and comfort to people's lives. In terms of psychological needs, the smart design of the building system enables information exchange between human and computer, and improves psychological services to users. Therefore, it is extremely important to satisfy users' needs in the application of interactive experience. The second is rational planning [30,34]. In the application of interactive experience technology, we should follow the principle of the reasonable use of time, space, and family members, so that the whole family can benefit from the smart design of the building system. The third is to build a model [20,72]. From the perspective of cognitive psychology, let users participate in the early design stage of smart buildings, put forward reasonable requirements, and provide a basic model for the interactive experience of the smart building systems.

Thirdly, in the smart building system, the user's real reaction determines the degree of acceptance of the smart building system. The user's feelings mainly depend on the following characteristics of product technology—stability performance, interaction mode, emotional expression, and so on [78,83]. Therefore, the smart building system should have a certain stability, and no matter how much user participation, all kinds of smart designs can perform their duties, adapt to more use environments, and ensure the stable performance of the smart environment. It should have a good human–computer interaction mode, and create a smart building environment that can be exchanged, so that the building is no longer a cold space; it should have human emotions, feel the emotional changes of users at all times, and adjust the home environment according to the changes, alleviate the mood of users, and be users' close friends.

5. Future Research Suggestions and Directions

The interaction design principle based on interaction experience is not only on the smart design, but also on the user's inner needs and motivations, especially how to realize the humanization of smart buildings and the effective communication between people, and to promote the development of a sustainable life; that is, to adhere to the principle of "people-oriented" smart design. A "people-oriented" approach is the development direction of various research content of smart buildings in the future. Only the interaction at the technical level and the spontaneous interaction between human and computer can create a more harmonious and friendly human–computer interaction environment for users, and the smart building system will develop towards a more intelligent, human-oriented, and personalized direction, providing more comfortable, safe, and effective smart services for home needs and promoting sustainable living.

In addition, with the emergence of 5G technology, people's use of the Internet and the Internet of Things will reach a new level—the ultimate experience of high efficiency, rapidity, and economy. The development of 5G smart buildings will receive more and more attention.

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sustainability

Review

Past, Present, and Future of Social Housing in Seoul: Where Is Social Housing Heading to?

Sang-Hyun Chung [1], Seung-je Kim [1], So-Youn Park [2] and Jun Ha Kim [3,*]

[1] Department of Architecture, Kwangwoon University, Seoul 01897, Korea; chun0069@kw.ac.kr (S.-H.C.); ksj@kw.ac.kr (S.-j.K.)
[2] College of Information and Technology Service, Kyonggi University, Gyeonggi-do 16227, Korea; sypark@kyonggi.ac.kr
[3] Department of Housing and Interior Design, Kyung Hee University, Seoul 02447, Korea
* Correspondence: junhakim@khu.ac.kr; Tel.: +82-10-7403-7487

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Abstract: In Seoul, a metropolitan city, affordable housing is a major issue. Since 2012, social housing has been implemented as a means to solve housing shortages in the South Korean capital. Various policies in different times have been applied, and Seoul came up with a unique form of social housing: providing housing to those in need. The purpose of this paper is to review the development of social housing in Seoul and to discuss policy implications. First, this paper defines the concept of social housing in Seoul by comparing that of social housing in Western countries. The major differences in the concept of social housing between Seoul and Western countries lies in the provider of social housing. The providers of social housing in Seoul are social economy actors, including non-private organizations and cooperative unions that work as agencies to pursue the public interest. In addition, this paper presents an overview of the historical development and specific features of social housing. Finally, a discussion is presented on the implications for social housings, including the need for the allocation of social housing throughout the city, the extended length of residence, and reliable financial support to social housing providers.

Keywords: social housing; social economy actors; Seoul; South Korea; sustainable development

1. Introduction

One of the most basic human needs is to attain a safe and comfortable place to shelter where one can live, rest, and flourish. However, obtaining decent housing is not guaranteed to everyone in modern-day South Korea, and further, acquiring one's own private housing seems to be a life-time but futile effort. Thus, people are consumed by the dream of owning their own homes. In the metropolitan city of Seoul, obtaining affordable housing options seems almost impossible because of various financial hurdles such as escalating housing prices and a housing supply shortage. Based on the Price-to-Income Ratio (PIR) in 2020, the number of years it takes to buy a house spending the entire income, people in Seoul Metropolitan City needed a sum of money equal to 24.58 years of income to buy an apartment unit in Seoul [1]. In 2020, the average housing price in Seoul was US $571,000 [2]. In addition, three challenges exist for young adults and newly married couples, who are emerging as new vulnerable strata of the population and are deprived of the possibility to own housing. These challenges are fewer full-time jobs, enormous education debt, and out-of-control housing costs [3]. In the midst of the crisis of not being able to own a house, social housing has become a significant alternative in solving housing problems for working but houseless Seoulites. Under the public housing umbrella, social housing in Seoul Metropolitan City intends to provide decent housing properties to people with just needs and rights at less than the current market price and for a more secure rental period.

According to the 2018 Organization for Economic Co-operation and Development (OECD) data, the proportion of social housing out of the total housing stock in various countries was as follows: Netherlands (37.7%), Denmark (21.2%), Austria (20.0%), the United Kingdom (16.9%), France (14.0%), Ireland (12.7%), and South Korea (6.8%) [4]. The average rate of social housing based on the OECD data is 7.9%. According to this data, the proportion of social housing in South Korea is lower than that of other European countries and the OECD mean [4]. To expand this viewpoint, it might be the right time to take a closer look and reevaluate South Korea's position regarding the social housing policy. By pinning down the meaning of social housing in Seoul, South Korea, and tracing how Seoul has been dealing with housing shortages for the past years, a renewed perspective to provide more affordable housing for more people can be offered. Therefore, the aims of this review paper are fourfold: (1) to review the definitions of social housing, (2) review the historical development of social housing, (3) investigate the current social housing situation in Seoul, and (4) discuss the future of sustainable social housing in Seoul.

2. A Review of the Definition of Social Housing

It is difficult to agree on a set of definitions for the term social housing. In fact, the concept of social housing and terminology itself differ in different countries. The OECD defines social housing according to Del Pero et al. (2016), who referred to it as a "residential rental accommodation provided at sub-market prices and allocated according to specific rules rather than according to market mechanism" [5] (p. 36). According to the United Nations Economics Commission of Europe, social housing is "supplied at prices that are lower than the general housing market and it is distributed through administrative procedure" [5] (p. 6). Furthermore, Scanlon, Whitehead, and Arrigoitia (2014), citing Haffner et al. (2010), noted that "a consistent identification of social housing is to provide living spaces to the households through administrative allocation process which gives priority to candidates with needs" [6] (p. 3). Taken together, common criteria of social housing include subsidies such as low-interest loans, below-market rent, long-term accommodations (long-term rent), and target groups with limited financial resources [7].

Understanding social housing as a broader concept, more specific and diverse terminologies exist that are bound to certain policies or administrations. To acclimatize social housing policy to the different situations and conditions of different countries, each country uses slightly different terminologies to refer to social housing. For example, in Denmark, "common housing" or "not-for-profit housing" is used, in Finland it is referred to as "government subsidized housing," and in England the terminology "social housing" is employed [8] (p. 7). This varied and slightly inconsistent use of terminologies for social housing in different countries makes it difficult for researchers to compare and contrast social housing schemes worldwide.

Kemeny's (1995) theory of housing rental systems is often used to define characteristics of social housing [9]. There are two models of a rental housing system: the unitary and dualist rental markets [9]. The unitary rental market defines that social rentals can compete with private rentals in the market without special protection. The dualist rental market implies that private rentals are dominant so that social rentals and private rentals cannot compete in the market and social rentals are operated as a safety net. In the dualist rental model, the providers of social housing are controlled by the government (p. 856) and the access to social housing is based on a means test [10]. Based on this theory, the social housing system in Seoul can be characterized as the dualist rental market since social housings are targeted for socially and economically disadvantaged such as people with disability, people receiving public assistance, or the elderly living alone who need some type of assistance.

In South Korea, the term social housing was first used in 2010, while the Enactment of the Seoul Social Housing Act was established in 2015 [11]. Since the use of the term social housing was relatively new and foreign to the public in Korea, the term "public housing" is more often used and familiar to the majority of citizens. The first public housing, built in the 1980s, still covers the role of social housing in Korea today [12]. The two terminologies, public housing and social housing, were used in diverse ways in different times in Korea, but served the same objective, namely, to stabilize housing shortages for those with need, especially low-income citizens [13]. Thus, researchers in Korea have often used the term public housing and social housing interchangeably.

Figure 1 compares the different understanding of public and social housing in Western countries and in Korea. Choi (2019) stated that, in Western countries, the concept of social housing encompasses public housing, while in Korea, social housing and public housing are classified separately under another broader umbrella term, namely, "public-social housing" [14] (please see Appendix A).

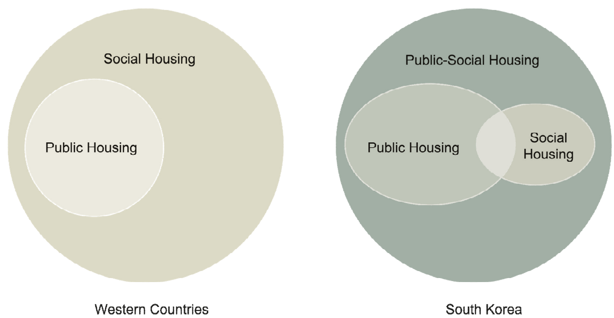

Figure 1. Comparison of the definitions of social housing in Western countries and South Korea.

There is a slight difference between the main entity of the ownership of public housing and social housing based on who owns the estate. Public housing is owned by the central and local government, while social housing is owned by various social economy actors including nonprofit organizations, cooperative unions, and social enterprises, resulting in the narrower scope of defining social housing in the Korean context. Because of the unique circumstances of public and social housing in Korea, this paper discusses these two terms separately. Furthermore, this paper focuses on social housing in Seoul, which originated through the Enactment of the Seoul Social Housing Act. This so-called "Seoul social housing" emerged through the collaboration of the public and private sectors to supply, administer, and manage social housing at a below-market price with an ensured tenure period [14]. Here, the private sector refers to actors in the social economy responsible for housing providers, which aim to pursue public interest rather than maximize profit [14].

3. A Review of Historical Development of Social Housing

3.1. A Brief History of Social Housing in Western Countries

Social housing emerged in the late 19th century, when charity and philanthropic organizations voluntarily helped marginalized people in European countries [15]. In England, which has a long history of social housing, a housing shortage resulted from the population explosion after the industrial revolution [16]. Some philanthropists and factory owners built residences for factory workers. Philanthropic organizations realized that a sole effort by private organizations to provide housing for factory workers could not solve the housing crisis. In most European countries, after World War II, housing shortages led the central and local governments to invest in supplying large-scale social housing to help the economy recover from postwar economic difficulties [15].

Nevertheless, how and why social housing emerged as a solution to housing shortages vary between countries. Especially in Western Europe and North America, people experienced severe housing problems due to rapid industrialization and urbanization. The most urgent issues were housing shortages, deteriorating housing environments, and increased housing costs [15]. To solve these problems, long-term rental housing supplied by the public sector and nonprofit organizations was implemented.

3.2. Historical Development of Social Housing in South Korea

3.2.1. Phase 1: The Beginning of Public Housing

Similar to what happened in many Western countries, industrialization and urbanization emerged in 1960 in South Korea. The urban population skyrocketed, and a shortage of housing arose [17]. At the time, a religious organization received money from a German charity and bought land and built housing for people who were forcibly driven from their homes by rapid urban development [17]. This particular housing can be considered the first public housing in Seoul, Korea. As mentioned, public housing in Korea is regarded as social housing in Western countries.

3.2.2. Phase 2: Growth of Public Housing

As economic growth progressed, housing problems became more serious. Since the 1980s, it has become one of the most pressing national problems [18]. In 1989, the central government supplied the first public housing to low-income families, which shared some common characteristics with social housing [12]. Until then, the term public housing was used, not social housing. The Korean government built a large-scale complex of apartment buildings in the remote and undeveloped regions of the city for public housing. Public housing was distinguishable from private housing as the term public housing was written on the walls of the apartment buildings. This public housing stigma resulted in the segregation of low-income families, as the fact that they lived in this public housing separated them from other neighborhood tenants, who were mostly well-to-do families. Since then, public housing has often been attached to a stigma related to poverty [19]. While the implementation of public housing might not have intended to bring about the physical exclusion of lower-income families, it had the negative effect of impeding social integration [19].

3.2.3. Phase 3: Challenges and Issues of Public Housing and the Need for Social Housing

There are three challenges of public housing. The first challenge for providing affordable housing to citizens was finding an adequate way to finance the projects. Public housing providers received low-interest loans from government-affiliated banks and were subsidized by the Government Housing Fund. However, the amount of support from the government was far below the actual construction and maintenance costs, which meant that capital financing had to be secured for new constructions. This lead to a housing shortage [19]. In particular, Seoul City Housing Municipal did not consider the varied real estate costs of different parts of the city, and with a uniform standard for financing, public housing projects faced increasing financial losses. Furthermore, financing private-sector projects was not easy. Housing prices continued to increase after the global economic crisis in 2008. In addition, newly started construction of public housing plummeted and the mortgage rate increased, which led to increased rental fees and housing costs for tenants [20]. The providers of private rental housing ran their rental business for profit, and their rental fees were higher than that of public rental housing, which made it even more difficult for economically disadvantaged groups to attain houses through private rental housing plans.

The second challenge for rental housing was recent demographic changes. As of 2018, 32% of all residents in Seoul lived in single households [21]. Among these single households, the elderly population also increased considerably from 4.0% in 2000 to 5.8% in 2018 [22]. This change in demographics is a significant link to further housing shortages. Because the public housing built in the past was designed for four-people households, there are not enough smaller units for single households [3]. Consequently, such small rental housing units are in great demand in response to current demographic household structure trends. In addition, young adults aged 20 to 30 years tend to leave the city of Seoul because of the high housing costs. The proportion of young adults who left Seoul increased from 29.7% in 2003 to 46.2% in 2014 [3].

The third challenge regarding rental housing is fierce opposition from the surrounding neighborhood comprising public rental housing. For example, in the 2010s, the Seoul office planned to build 3300 apartment units to provide as public housing; however, strong resistance from local residents, municipality parties, and politicians stopped the plan [3]. Reasons for the opposition include concerns for local slumming, violation of the personal right to have views unblocked by apartment buildings, and increased traffic problems [3]. Furthermore, the number of complaints against constructing public rental housing peaked in 2018–2019 [23]. This indicates that building more new public housing is hampered, resulting in a shortage of public rental housing to be offered to those in need.

Taken together, providing public housing by the governments reaches its limit and the government and private sector need to revisit the public housing policy in order to solve housing problems in Seoul. It was supposed to supply affordable and stable housing to citizens in need, and the newer term and concept of social housing has now emerged to compensate for existing public housing.

3.2.4. Phase 4: Birth of Seoul Social Housing

Since 2012, the social housing plan has been taking a more progressive shape. Seoul was the first city in South Korea to provide social housing and various support policies for houseless citizens [24]. Interestingly, in 2012, the Cooperative Union, one form of private-sector organization, took initiatives to supply social housing [24]. The Cooperate Union further developed social housing polices, and Seoul City Housing Municipal in the public sector followed this private-sector initiative [25]. Table 1 summarizes the progress of social housing development [26]. In 2012, Seoul established the "Social Investment Fund" and implemented policies that provided subsidies and land loans to social housing providers. In 2015, the Enactment of the Seoul Housing Act was set out as the first decree for social housing. Based on this enactment, the concept of social housing was finally concretely defined to mean rental housing for socially and economically disadvantaged people. It was to be supplied by social economy actors such as nonprofit organizations and the Cooperative Union. According to this enactment, social housing was located in a socially mixed environment that aimed to solve the problem of previously built public housing blocks of geographically segregated public housing estates. In 2018, the Housing and Urban Guarantee Corporation (HUG) was established to help social housing providers provide financial support and consultation for the social housing business.

Table 1. Development of social housing in Seoul.

Year	Events
2012	Establishment of Social Investment Fund
2015	Enactment of Seoul Housing Act
2016	Opening of Total Support Center for Social Housing
2017	Establishment of Seoul Social Housing Ritz
2018	Establishment of Land Support Ritz Establishment of Korea Housing and Urban Guarantee Corporation (HUG)

4. Seoul Social Housing

4.1. A Category of Public Interest Housing in Korea

Although this paper focuses mainly on Seoul social housing, it is worth reviewing the bigger picture of public social housing in South Korea. Currently, there are three categories of public–social housing: public housing, semi-public housing, and social housing (see Table 2) [27]. For public housing, only the public sector such as the central and local governments can provide the budget and funds to supply housing to citizens in need of rent below the market price. There are two ways to do this: (1) buy land and build housing on that land, and (2) buy existing housing from the market and supply housing. Regarding semi-public housing, private companies supply housing to the public who have no eligibility to rent housing at a lower price than the market. These private companies are endowed with two benefits: borrowing low-interest loans from the government and receiving government favor such as tax cuts or Floor Area Ratio (FAR) advantages, meaning that the total floor area can be increased. With respect to social housing, social economy actors supply housing to the public in need. These social economy actors can receive financial support such as a low interest rate from the public sector through the public–private partnership, in which the public sector provides financial benefits to providers to supply social housing. Social housing targets moderate-to-low-income tenants who earn a higher income than those in public housing. The financing and eligibility for social housing are detailed in the next section.

Table 2. Different types of public–social housing in Seoul.

	Public Housing	Semi-Public Housing	Social Housing
Supplier	Central and local government	Private company	Social economy actor
Financing	Public funds	Private capital or loans	Public & private loans
Eligibility	1–4 quartile income of city workers	None	Lower than 6th quartile
Rent	30–80% of the market price	Below the market price	Less than 80% of the market price
Residency	10~20 years	10 years	10 years

Figure 2 presents the allocation of public housing and social housing in Seoul [28]. In general, the locations of public housing and social housing do not tend to overlap each other and social housing is more likely to be placed evenly throughout the city, whereas public housing is clustered in a certain part of the city. In addition, based on the available data of 2017, the number of public housing units is estimated at 271,308 [29], while the number of social housing units is 239 [14].

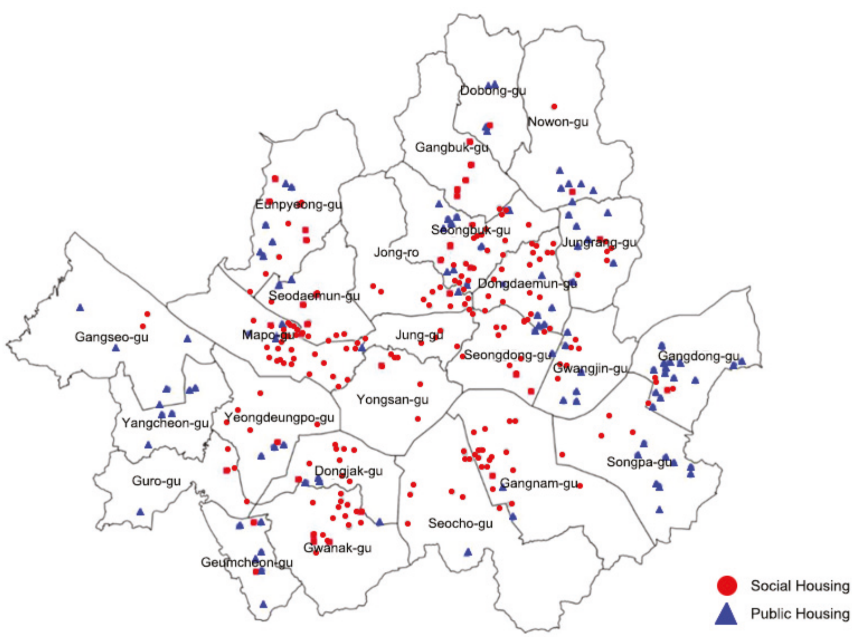

Figure 2. Allocation of public housing and social housing.

4.2. Models of Social Housing

There are three types of social housing models from the housing provider's side: Land lease housing, renovation of nonresidential buildings, and renovation of empty houses (see Table 3). For land lease social housing, social housing providers borrow land owned by the Seoul city government for 30–40 years at a low interest rate and build housing on that land [28]. Regarding the renovation of nonresidential buildings, social housing providers renovate old nonresidential buildings such as hostels or dormitories with financial support from the city government. Financial support is determined by the rental period. In terms of the renovation of empty houses, social housing providers renovate homes that have been abandoned for more than six months. The city government subsidizes construction fees to renovate empty houses according to the rental size. The target group for the three models of social housing is the vulnerable working population such as young adults, newly married couples, or low-income families. Housing is allocated through an income test to mostly middle-to-low-income households. Rent for all three types of social housing models is less than 20% of the market price [28]. Eligibility for all three types of social housing is determined by employment status and income [30]. Specifically, as for a single-person household, mean monthly income is less than US $3,882, and with respect to two-person households or above, mean monthly income is less than US $4,840. As for a newly married couple, the eligibility for mean monthly income is less than US $5,832.

Table 3. Types of social housing.

	Land Lease	Renovation House	Reviving Empty House
Rent	20% less than the market price	20% less than the market price	20% less than the market price
Tenure	Up to 10 years	6–10 years	6–10 years
Eligibility	Employed and the mean monthly income is 70–100% or less	Employed and the mean monthly income is 70–120% or less	Employed and the mean monthly is income 70–120 or less

4.3. Architectural Aspects and Allocation of Housing Units

To date, the total number of social housing stock units in Seoul is 1275 (see Table 4). Of the three types of social housing, the number of land lease houses tended to increase, while renovation buildings and revival of empty houses decreased. Figure 3 shows the allocation of social housing in the city of Seoul. More social housing is located in the northern part of Seoul than in the southern part. The northern part of Seoul is an old town and the southern section is a new town. The poverty rate in the northern part and the southern part is 3.98% and 2.68%, respectively [31], implying that the northern part has relatively more poor people. This condition may affect that more social housing has been built in the northern part.

Table 4. Social housing stock (units: housing units).

Year	Land Lease	Renovation House	Reviving Empty House
2015	22	0	80
2016	114	37	152
2017	80	145	14
2018	272	89	0
2019	209	61	0
Total	697	332	246

Reference: Choi (2019). New providers of affordable housing. Housing Welfare Conference.

Figure 3. Allocation of Seoul social housing.

5. Future Directions for Sustainable Social Housing

Korean social housing was launched to solve housing problems and create a more sustainable social housing scheme. The social housing system systematically operates and manages the housing community by establishing the self-government rules written by the tenants and the management rules as a management entity to revitalize the autonomous resident community. In addition, the social network was restored by promoting the revitalization of sustainable and self-sustaining communities and by establishing community-based social housing and regional regeneration anchor facilities. The social housing is mandated by legislating the composition and operation of communities and people-centered living spaces are being operated. From the economically sustainable perspective, the burden of land purchase costs was relieved when developing social housing projects by reinforcing social publicity through long-term lease of land.

Nevertheless, some issues still need further consideration. First, social housing needs to be equally located throughout Seoul and not concentrated in only one region. Geographically grouped locations separate the tenants of social housing from other private-housing neighborhoods [32], creating a segregation effect. One way to avoid this undesirable circumstance is to locate social housing sparsely throughout the entire city, which would ensure that no region or neighborhoods are tagged with the negative connotation of social housing. This strategy will decrease the segregation effect, because the tenants of social housing will be living in every neighborhood in Seoul. For example, in Vienna, Austria, social housing accounts for 43% of all housing options and is distributed throughout the city [14]. However, in some cases, limitations seem to exist for this mix-in strategy. Residents of private housing often mark their private property with iron fences on public pedestrian passages to prohibit the residents of public rental housing from trespassing in South Korea [19]. Even worse, residents of social housing and private housing on the same estate divide the use of elevators, which results in segregation within a property. This phenomenon is of great concern to all involved in social and communal living. Such a problem is not limited to South Korea. For example, in Belgium, residents of social housing were seen as being problematic, because they often did not pay rent and vandalized properties of social housing [33]. A key solution to this problem might be the concept of a "social mix," which is the mix of social and private housing in one building [34]. Socially mixed social housing does not only mean physical buildings geographically spread equally throughout a region, but also an identity of being a "mixed" community of social and private housing [35]. A live example can be found in Belgium, where the Minister announced the policy document requesting social mix for social housing communities and a whole society for all citizens to acquire a life of quality [33]. Supporters of the social mix believe that if social housing is indistinguishable from private housing, no stigma will be attached to tenants of social housing. Ultimately, the intention is to build social housing with residents of various demographic backgrounds and neighborhoods a harmonious and pleasant place to live, leading to social integration.

Second, the length of the residential period needs to be extended to more than ten years to secure residential tenancy. For social housing in Seoul, contracts are renewed every two years up to five times, meaning that a tenant can live in social housing for up to ten years if eligible. This ten-year tenancy time limit does not guarantee that tenants may be able to live in the place they want without having to move. However, assured housing tenancy must be reflected in social housing policies, so that tenants can obtain the same quality of life with guaranteed tenancy as those with private housing. Guaranteed tenancy is related to lower rent burden and stability [36], which enables the reliable planning of family matters. In Singapore, the government leases social housing for up to 99 years, which provides residents with assurance and is considered as good as a permanent home [37]. Likewise, with reference to Singapore, the state government of Hawaii in the United States proposed the utilization of state-owned lands to build social housing and sell it to the public, especially to low-income families and non-homeowners without a means test for 99 years [38], prioritizing low-income families. However, some bring up the notion of equity in housing security [39]. For example, people on a housing wait list may not be able to obtain social housing if a tenant does not move out within scarce social housing resources.

Third, it is necessary for tenants to participate in the management of social housing. It is widely considered good practice for tenants of social housing to express their opinions [40]. Tenants' involvement in social housing provides a high level of satisfaction with social housing services and increases their self-esteem, as they are able to participate in and contribute to community living [41]. This type of participation created a saving of up to 118 million euros [41]. For example, in Denmark, based on the 1984 Law on Tenants Democracy as one of the key principles of social housing, residents manage each housing estate [6]. In this way, tenants' participation in the management of social housing can prevent them from being marginalized [42].

Last, a reliable financing system to construct and manage social housing is needed. The rent for social housing in Seoul is almost as high as that for private rental housing. The rent for social housing does not cover the current costs of construction and maintenance; therefore, without the government's greater contribution, social housing providers cannot help but reduce their revenue or increase rent. However, currently, even the central government does not provide funds to social housing providers, worsening this situation. At the moment, only local authorities (municipalities) provide financial support. To lower the rent for social housing, the local government must establish a set of systems through which providers can supply social housing at an affordable price. One way for the government to overcome this obstacle is to reduce the land value by turning land use to a form of public land for social housing providers at below-market prices [6] (p. 327).

6. Conclusions

In Korea, before the concept of social housing emerged in 2012, the public and private sectors independently took charge of providing housing. Social housing allows collaboration between the public and private sectors to supply housing, meaning that the private sector receives benefits and assistance from the local government to build such housing. Social housing in Seoul fills a gap in the housing supply for those who are not eligible for public housing but still have insufficient income to rent at market prices. In this sense, social housing in Seoul is an alternative housing system to provide a safety net for houseless Seoulites.

In order to be more sustainable in providing social housing in the future, the following four issues should be considered. First, with the preparation of legal basis at the central government level, all social-housing-related parties basically follow the ordinances of Seoul City, but local governments in Seoul should establish suitable ordinances in accordance with their situations. Second, all social housing projects undertaken in Seoul should be thoroughly analyzed to develop new sustainable business models to diversify supply methods. Third, Seoul city government needs to support revitalization of community based on "social mix," which realizes the social values and activates various community-based communication programs in social housing, and this will contribute to create local-related jobs centered on services that are enjoyed on a daily basis. Finally, to cultivate and strengthen the capabilities of social housing providers, effective education on social economy, housing design, construction, operation, and finance is needed, and to continuously discover the improvements in managing social housing, opinions from the residents and providers through regular meetings such as forums and seminars should be collected.

Lastly, this paper will discuss some limitations and suggestions for future studies. This study analyzed only one city—Seoul—but it would be interesting for future studies to compare other countries' social housing forms with that of South Korea, in an international context, to examine the differences and similarities. In addition, this study does not include various stakeholders' perceptions, such as that of residents' organizations or directors of the social housing associations. This limits the presence of multidimensional perspectives of social housing. Future research is needed to include both residents and providers of social housing.

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Appendix A

Figure 1: In the process of translation of the original diagram, Choi used the term "public/interest housing." However, the authors suggest that the term "public-social housing" be used to avoid confusion stemming from the interchangeable use of the term public housing, which is categorized and understood as a subcategory of social housing in western countries. The authors believe the term public–social housing reflects the uniqueness of public housing and social housing co-existing in the Korean context. To prevent confusion from using social housing as a generic term, the authors here use the more specific term "Seoul social housing." The generic term social housing makes it difficult to explain the Korean situation because of its different context, definition, and specification.

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Strategy of Water Distribution for Sustainable Community: Who Owns Water in Divided Cyprus?

Eun Joo Park

Department of Architecture and Architectural Engineering, Seoul National University, Seoul 08826, Korea; ej_park80@hotmail.com; Tel.: +82-(0)10-9863-0528

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Abstract: Although it is completely surrounded by the Mediterranean Sea, the island of Cyprus has long suffered from water problems arising from irregular rainfall, leading to sustained political conflict conditions for a long period. Water scarcity is likely to become a major issue, thus a range of options for water catchments should be examined and trialed. This article explores the connection between ownership of water and water management in a divided territory to gain an understanding of how politics are involved in water conflict. By investigating the water situation in Cyprus, this study aims to evaluate the strategies that can ensure the sustainability of new water networks for domestic and irrigation needs. This understanding can be used to minimize the gap between water supply and demand to provide water stressed countries with sufficient, safe, and reliable water for their domestic and irrigation needs. The research proposes a reinterpretation of the extraterritorial conditions of contemporary Cyprus and a plan to realign the island's water system through the creation of a new post-national territory. Thus, the study presents a vision for a sustainable water supply. In addition, the study discusses strategies and actions for water distribution networks with consideration of political and social issues to provide a potential new vision for future urbanization.

Keywords: water distribution; water war; conflict; ownership; divided Cyprus

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1. Introduction

1.1. Background and Purpose

Water is a precious resource. The growing global population coupled with climate change means that water supply is one of the most significant challenges facing the world today. It is expected that by 2080, half of the world's population will experience water shortages [1]. Access to and exploitation of water resources has always been a challenging issue, causing conflicts, struggles, and even war within and between societies and countries. In the 1980s, intelligence of the United States Government identified 10 countries where water wars could break out, with Cyprus listed among those countries [2]. Cyprus suffers from the highest level of water stress in Europe, particularly during years of excessive drought [3] (see Figure 1), and by 2025 will experience ongoing water shortages. Water shortages are crucially linked to Cyprus's economic activities and are exacerbated by population growth, tourism, and the activities of other industries. Another contributing factor to Cyprus's limited water supply is the island's over-reliance on precipitation; thus, its water resources are particularly vulnerable to future changes in the volume and distribution of rainfall.

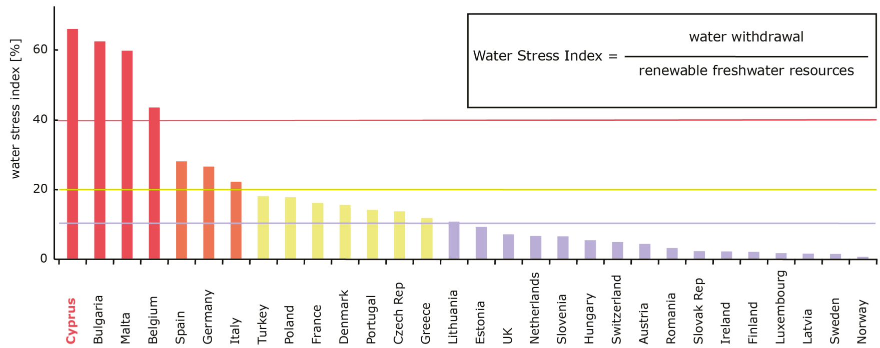


Figure 1. Water stress levels in Europe, showing Cyprus as the most water stressed country [4].

Having insufficient water resources can increase political tensions within and across countries, and water becomes a political tool for negotiation between countries. The deliberate destruction of dams and pipelines and the pollution of drinking water is a method used by governments and terrorists to engage in hostile martial action. However, while there is no historical evidence that Cyprus has ever engaged in water wars, the island's division between Greece and Turkey has been a source of great conflict, meaning that Cyprus is an excellent case for examining how an integrated policy can help to ensure safe water supply in areas of conflict. Water shortages have been a severe problem for both the Greek and Turkish Cypriot communities, and joint action on securing water supply could resolve the island's ongoing political division. Thus, possible scenarios of collaboration between the two parts of the island could lead to a "water peace" [4].

It is important to understand and manage uncertainty about the future impacts of climate change and drought on water catchment systems around the world. Moreover, there are major challenges in predicting water catchment responses associated with an uncertain future in terms of climate change and land management in divided territories. However, little research has been conducted in the context of Cyprus on its major cause of water scarcity: climate change and drought, which peaked in the winter of 2007, 2008, and 2018 [5]. In addition, there have been no studies in the context of Cyprus on spatial and temporal changes in water resources and sustainability. Thus, this research aims to suggest new strategic actions that can be taken by Cyprus to increase the sustainability of its water management and to investigate the effect on water demand and supply that arises from the political status of disputed territories. In addition, the study suggests future directions for water distribution that will allow sustainable water supply in other water stressed countries.

1.2. Research Methods and Procedures

The term "water wars" refers to conflicts in different regions arising from disputes over the use of fresh water, and describes the struggles to supply water for domestic and irrigation needs. This research analyses the causes and consequences of water conflicts, identifies the problems associated with existing water management practices, and proposes alternative strategies for water catchment and distribution in divided Cyprus. The research uses Cyprus as the study context, because it provides an example of a state that operates in a climate of political dispute. The principal goal of this study is to identify the causes and consequences of the water conflict in Cyprus, and present a strategy for improving the water distribution networks of the island with the final aim of presenting important strategies for improving water management and sustainable new water networks for domestic and irrigation water needs in other water stressed countries like Cyprus.

To achieve the objectives of this research, the study seeks to answer the following questions:

- What are the main causes of water scarcity?
- What are the priorities, delays, and causes related to water demand?
- Does political conflict lead to water conflict?
- What type of water management can lead to less water conflict in different regions?
- Which group or organization is in charge of controlling water use and plays the key role in maintaining, sustaining, and controlling the water supply?
- How can different causes and consequences of water conflicts be classified?
- What systems could allow communities to use water peaceably and sustainably now and into the future?

The methodology employed in this study addresses new methods of water collection and distribution for domestic and irrigation needs. The research also analyses whether new architecture for water collection and distribution can avert water conflicts. The research also proposes a new architectural concept that is both the object and the method of enquiry.

Practices in water management in Cyprus are analyzed based on existing data and previous research. The study envisions and suggests how architectural design can be used to devise strategies for new urbanization in Cyprus (Figure 2).

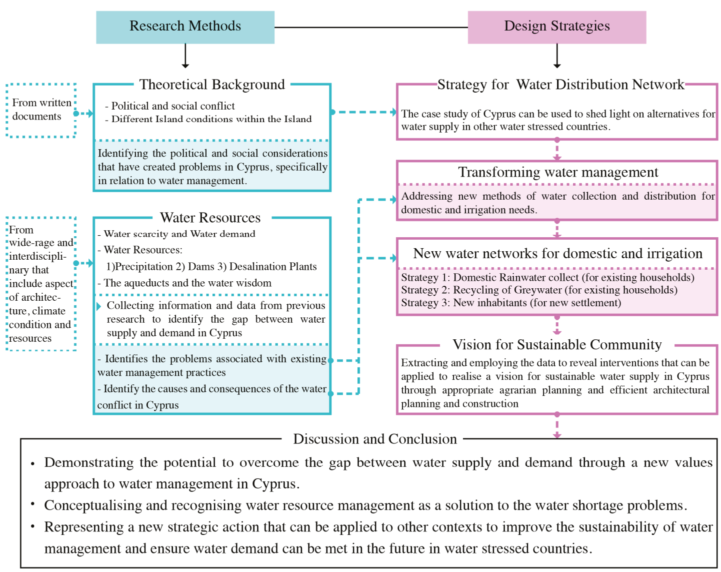


Figure 2. Methods and procedure of the study. Source: author's drawing.

2. Theoretical Background

2.1. Related Works

The term "water shortage" refers to insufficient quantities of fresh water to meet water demand, resulting in the imposition of substantial restrictions [1,2,4–8], which can affect social conflict and economic development. There is a growing body of literature examining the impact of climate change [3] on water resources at the global and continental or national level. However, relevant simulations on a local scale still face additional challenges caused by the reduction of procedures and uncertainties [9,10].

Many studies have dealt with water shortages in relation to the problem of water resources [11–14] and climate changes [3], and have emphasised the importance of water management [15] and policy [4]. Wars have already been fought in many regions of the Middle East over the desire to gain sovereignty over water sources [11]. The Mediterranean region is among the areas that will be most affected by climate fluctuations. The availability of water resources and the water use level highlight the current and future challenges and opportunities for water management [10]. It is speculated that water may become the cause of future conflicts, with the term "water wars" [2] perhaps being the first alarmist recognition of how water scarcity may lead to widespread social disruption [16]. It is widely accepted that the access to and exploitation of water resources has always been a challenging issue, causing water conflicts, struggles, and even wars within and between different societies and countries. The term "water wars" refers to conflict among groups, societies, or countries over gaining access to water supplies [4].

Some authors have recognized that wastewater production can address the gap between clean water demand and supply [4,13,15]. The causes of water shortage include the uneven spatial and temporal distribution of water resources and increased demand for water; thus, the development of alternative water sources, such as recycled water, brackish water, and rainwater [17], is essential for closing the gap between supply and demand [18]. As an alternative, it has been shown that water recycling in agriculture provides the benefits of increasing water availability for other activities, such as domestic and industrial use; reducing competition among users; and preventing the overexploitation and decomposition of natural bodies of water. This perspective appears to be evolving in many countries around the world [19–22] seeking to cope with the growing water demands for water and protect their water resources from overexploitation in the face of ever-increasing populations.

To produce an appropriate urban water supply, it is necessary to improve the management and operation of domestic water supply networks by simultaneously identifying challenges and opportunities for current and future network management. To date, the sustainable use of water resources faces great challenges posed by population growth, weak economic conditions, increasing demand for water, the need to ensure food security, poor quality, and aging infrastructure [23]. These challenges have not been effectively addressed in existing water governance plans, highlighting the need to develop more sophisticated water management plans in response to changing conditions and requirements. Current insights into water management consider background expertise in the field and include government services and agencies, the private sector, and the public [24,25].

Water regulates ecosystem functions, preserves the quality of the environment, facilitates human health and well-being [26], and plays an important role in supporting life [27,28]. The issue underscores the need for revised water management, especially in areas subject to demographic changes and climate vulnerability, to ensure a sustainable and secure water supply. This study highlights and discusses situations and possible solutions, such as advanced technical solutions and practices and alternative, more efficient water usage, addressing the growing environmental and health requirements, as well as new conflicts among water users. However, the consideration of water catchments and distribution through urban networks systems to improve safe water supplies is lacking. Thus, this research has three principal areas of focus:

(1) The investigation of the political and social conflict in Cyprus to understand theoretical background of disputed Cyprus
(2) The data collection and analysis of water resources to find ways of reducing water demand
(3) The proposition of a preliminary conceptual design of water catchment and distribution that provide a sustainable vision of safe water supply.

2.2. Disputed Cyprus

2.2.1. Political and Social Conflict

From approximately mid-2 BC, Cyprus was dominated by different foreign countries almost without interruption until 1960, when the former colony became independent from Britain. Thus, for almost two millennia, external powers dominated the island and its people. In December 1963, violence broke out between the Turkish and Greek Cypriots over who would gain control of the island country, leading to the establishment of the United Nations Peacekeeping Force in Cyprus (UNFICYP). However, despite the role of the UNFICYP, Greece and Turkey were at risk of going into war in 1964 and in 1967. Thus, the Cyprus dispute was a conflict between the Turkish Cypriots and the Greek Cypriots over which ethnic community would gain control of the island country. Cyprus was divided in 1974, with the Greeks controlling 63% of the territory, and 37% of its territory (the northern third of the island) occupied by Turks, causing a de facto division of the island [13]. A military invasion by Turkey led to a partitioning of the island, the displacement of many of its inhabitants, and eventually a declaration of independence by the north in 1983 [29] when the Turkish Republic of Northern Cyprus declared independence from the Republic of Cyprus.

The small island of Cyprus is currently subdivided into four communities: the Republic of Cyprus, Turkish Republic of Northern Cyprus, a buffer zone between the two controlled by the United Nations, and two bases under British sovereignty [30]. The political system of Northern Cyprus is a semi-presidential democratic republic. The events that led to the current division of Cyprus and the resulting political situation are still matters of ongoing dispute (see Figure 3).

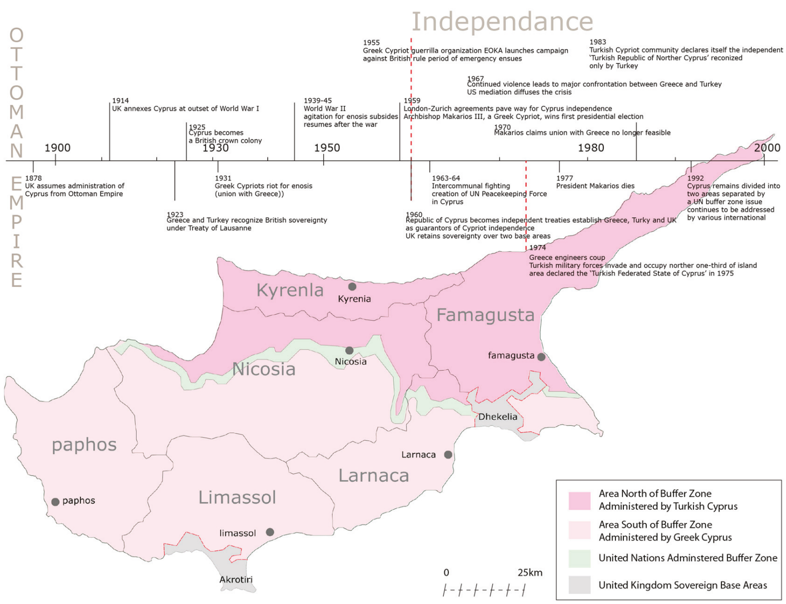


Figure 3. Political history of Cyprus. Source: author's drawing.

2.2.2. Islands within the Island

Cyprus is an island country located in the north-east of the East Mediterranean basin. With an area of 9251 km^2, Cyprus is the third largest island in the Mediterranean. As a result of the division, Cyprus has many different island conditions (see Figure 4). This section present the various island conditions to obtain an understanding of the political status of water management in divided Cyprus.

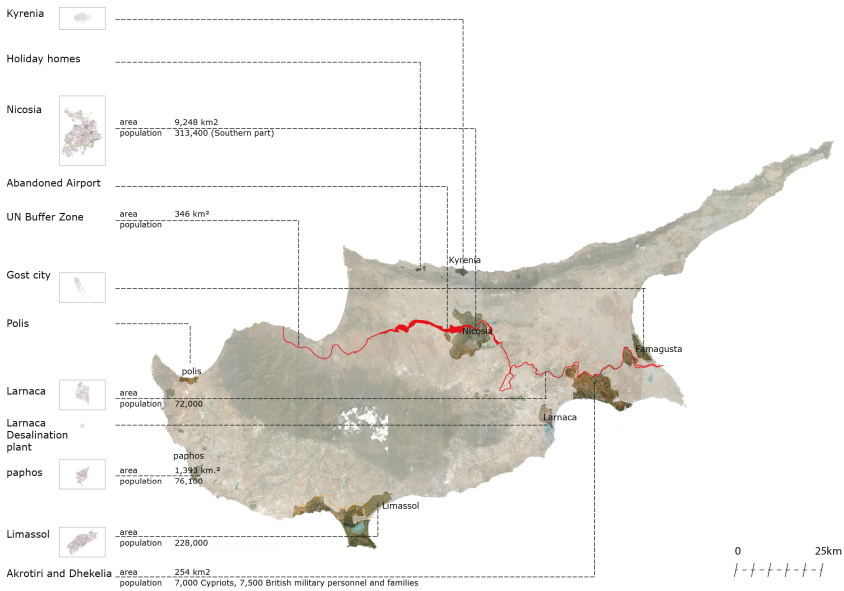


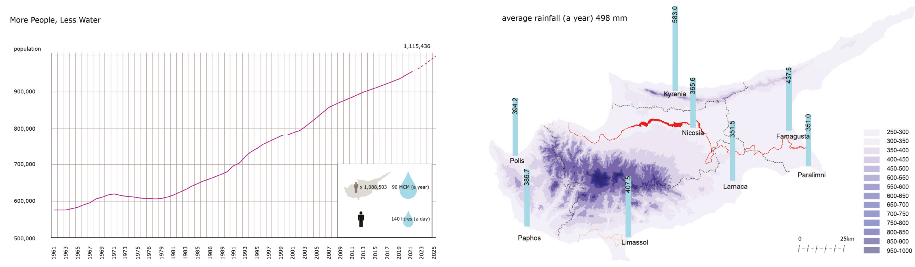
Figure 4. Island cities in divided Cyprus. Source: author's drawing.

The island conditions within divided Cyprus are as follows [29,31]: (1) Nicosia is the capital city of Cyprus, and is the only divided city in any European country. It is characterized by its political boundaries, including a wall around the city and the buffer zone that divides the northern and southern portions of the country. (2) Nicosia International Airport was used in World War II but was abandoned following the Turkish invasion in 1974. Following cessation of hostilities in 1974, it was declared a United Nations protected area and now lies within the United Nations buffer zone separating the two sides of Nicosia. (3) The Varosha quarter of Famagusta in Cyprus was one of the most popular holiday destinations in Europe. However, in 1974, what was once dubbed the "Millionaire's Playground" suffered a number of casualties arising from the Turkish invasion that led to the division of Cyprus into north and south. (4) Akrotiri is a large Royal Air Force base in Cyprus that functions as a British foreign territory and is managed as a Sovereign Base Area. Britain has a treaty with Cyprus that guarantees British access to Akrotiri under any circumstances. (5) Cyprus achieved independence from Britain in 1956 after a protracted struggle by Greek Cypriots seeking unification with Greece. However, Britain retained two military base areas—Ormidhia and Xylotymbou—surrounded by territory belonging to the British Sovereign Base Area of Dhekelia.

3. Water Resources in Cyprus

3.1. Water Scarcity and Water Demand

Cyprus is currently suffering from a severe water shortage arising from drought in 2007, 2008, and 2018, resulting in its streams and reservoirs literally running dry [32]. The gap between water supply and water demand is increasing because of the growth of the local population, migrants settling in Cyprus, and tourism. For instance, in 1995, the population was 666,313, with a water demand of 132.5 million cubic meters (MCM). By 2000, the population had increased to 697,549, and water demand was 265.9 MCM, and by 2012, the population had reached 865,878, and water demand was 275 MCM [33,34] (see Figure 5a).



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

Figure 5. (**a**) Population growth by 2025; (**b**) Precipitation. Source: revised from [32].

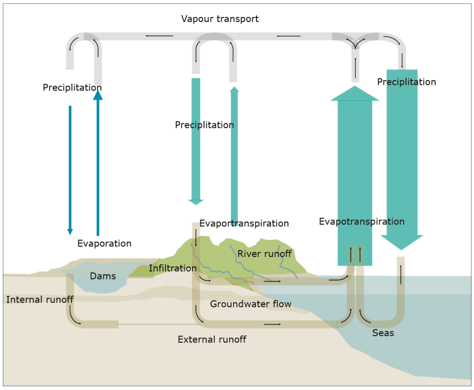
Until 1997, the main source of water in Cyprus was rainfall, with the island relying heavily on rain to supply water. However, the average annual rainfall has decreased over the years. According to a series of observations, the average annual precipitation, including snowfall, has decreased from 503 mm in 2000 to 463 mm. Between 2001 and 2004, exceptionally heavy annual rainfall increased water reserves, with supply exceeding demand, allowing total storage in the reservoirs to increase to a record high at the beginning of 2005. However, since then, the annual supply has fallen to 498 mm, while demand has increased from local population growth, foreigners relocating to Cyprus, and an increasing number of tourists [35] (see Figure 5b).

There is an urgent need to resolve this problem. In a first step to identify ways in which to minimize the gap between water supply and demand in Cyprus, this section explores the following related factors: (1) precipitation and water cycle, (2) dams and desalination plants, and (3) water consuming sectors.

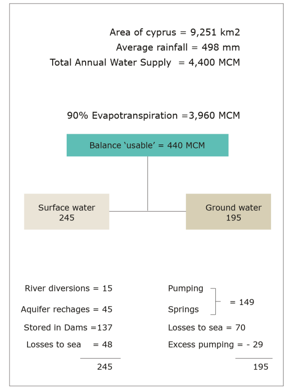
3.1.1. Precipitation and Water Cycle

The cycle of water movement from the atmosphere to the earth in the form of rain, snow, or hail and back to the atmosphere through evaporation is referred to as the water cycle [36] (see Figure 6a). The quantity of water falling over Cyprus's total surface area is estimated to be 4400 MCM [37]. However, only 10% (440 MCM) is available for exploitation, because 90% returns to the atmosphere as direct evaporation and transpiration. The remaining 440 MCM infiltrates the earth through the pores and fractures of rocks and recharges the groundwater. Of this, 195 MCM reappears on the ground surface through springs. Of the 245 MCM of surface water, 137 MCM is stored in dams and reservoirs, the total capacity of which is presently 300 MCM. During winter and spring, when the rivers have a surface flow, 182 MCM of water is used to irrigate the nearby fields [36] (see Figure 6b). A total volume of 48 MCM of surface water flows into the sea. In addition, approximately 149 MCM of water is pumped from aquifers, with 45 MCM flowing into the subsurface through the aquifers and being lost to the sea.

The values provided above represent the water balance in Cyprus when there is an average annual rainfall of 498 mm [37]. The rainfall in Cyprus is unevenly distributed geographically, with the highest level of rainfall being in both mountain ranges and the lowest level in the eastern lowlands and coastal regions. In addition, given frequent droughts that can span from two to four years, there are great variations in rainfall. Further, approximately one-third of the underground water storage flows into the sea.



(a)



(b)

Figure 6. (**a**) Cyprus water cycle; (**b**) Cyprus water balance. Source: revised from [35,37].

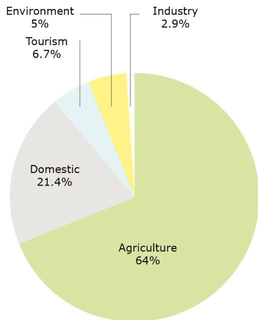
3.1.2. Dams and Desalination Plants

Severe water shortages and droughts in Cyprus have forced the government to adopt the method of seawater desalination to increase drinking water supplies and remove dependence on rainwater to provide the entire population of Cyprus with sustainable access to safe drinking water. Dams are the main source of water used for domestic and agricultural purposes. There are a total of 108 dams and reservoirs in Cyprus, with a total water storage capacity of approximately 333 MCM [38]. The government accelerated the construction of additional dams on the stream-like rivers of Dhiarizos, Akaki, Peristerona, Karyotis, and Tylliria. It then completed the Nicosia and Limassol sewage systems, which recycled sewage water for irrigation, issued licences for the construction of desalinisation plants, and initiated a water conservation campaign.

Despite these efforts, a series of drought years have left the dams in Cyprus almost empty [39]. Thus, water desalination plants are gradually being constructed to deal with the ongoing drought of recent years. Since 2001, the government has invested heavily in creating desalination plants, which supply almost 50% of domestic water. Efforts have also been made to raise public awareness and make domestic water users more responsible for the preservation of this increasingly scarce commodity [37]. Desalination can meet up to 50% of demand in some regions, but others rely on rainfall, reduced irrigation, and the tapping of aquifers [40].

3.1.3. Water Consuming Sectors

The two principal water consuming sectors in Cyprus are irrigation and domestic use. In 2004, the agriculture sector accounted for approximately 69% of total water use, while the domestic sector accounted for 20%. Other water consuming sectors included tourism (5%), industry (1%), and amenities (5%) of water demand (see Figure 7a). The total water demand in Cyprus was 265.9 MCM annually [41]. In 2018, a large portion of the economy of Cyprus relied on tourism, and to some extent, agriculture, which is the largest user of water on the island, currently accounting for 64% of the consumption of Cyprus's water resources. Other major water consuming sectors are domestic use (21.4%), tourism (6.7%), and industry (2.9%) [4] (see Figure 7b). The total water demand in Cyprus was 302.3 MCM, and it is estimated that by 2025, water demand in Cyprus will increase to 313.7 MCM, mainly because of increasing use of domestic water and the expansion of tourism [42]. This presents many challenges for water management and conservation in Cyprus [41].



(**a**)

The Total Annual Water Demand all over Cyprus for the year 2018 is estimated to be 302.3 million m3 (MCM) and is distributed as follows:

AGRICULTURE	193.47 MCM	64.0%
DOMESTIC	64.69 MCM	21.4%
Tourism	20.25 MCM	6.7%
INDUSTRY	8.77 MCM	2.9%
ENVIRONMENT	15.12 MCM	5.0%
TOTAL WATER DEMAND	302.3 MCM	100%

(**b**)

Figure 7. Water demand in Cyprus: (**a**) Water usage by sector; (**b**) Total water demand and distribution in 2018. Source: revised from [4,41,42].

3.2. Water Resources in Cyprus

3.2.1. Water in Southern Cyprus: Desalination Plants

Despite the construction of desalination plants in the southern Greek sector of Cyprus, the island faces an acute water crisis that has been aggravated by several years of drought and an increased demand for water by the growing population. The ongoing water crisis is also beginning to affect tourism, one of the island's main industries, thus risking revenue from the three million tourists who visit Cyprus each year [43]. The extended drought in Cyprus has resulted in unsatisfactory levels of water stored in dams and created the need to build seawater desalination plants to supply drinking water to the large urban and tourist centers without relying on rainfall. To meet demand, in the early 1990s, Cyprus began building desalination plants, which now supply most of the drinking water in the southern part of the island. There are currently four desalination plants in operation: Dhekelia, Limassol (Episkopi), Vassilikos, and Larnaca. In addition, the construction of a desalination plant in Paphos was expected to commence at the end of 2019 [44] (see Figure 8). The desalination plants in Dhekelia and Larnaca meet a significant portion of the drinking water needs for Nicosia, Larnaca, and Free Famagusta, with a total production capacity of at least 32.8 MCM annually. The desalination plants of Limassol (Episkopi) and Vassilikos meet a significant proportion of the drinking water needs of Limassol and some of the needs of Free Famagusta, with a total production capacity of at least 32.8 MCM annually [32,44]. Desalination plants contribute greatly to solving the water problem in Cyprus. However, the total capacity of desalination plants does not meet demand during severe drought because of the illegal and uncontrolled overextraction of groundwater, tragically leading to the permanent and irreversible depletion of underground aquifers and irreversible salinization of the coastal aquifers [4]. Thus, sustainable management of water resources is needed to help Cyprus effectively address water shortages during drought periods every year.

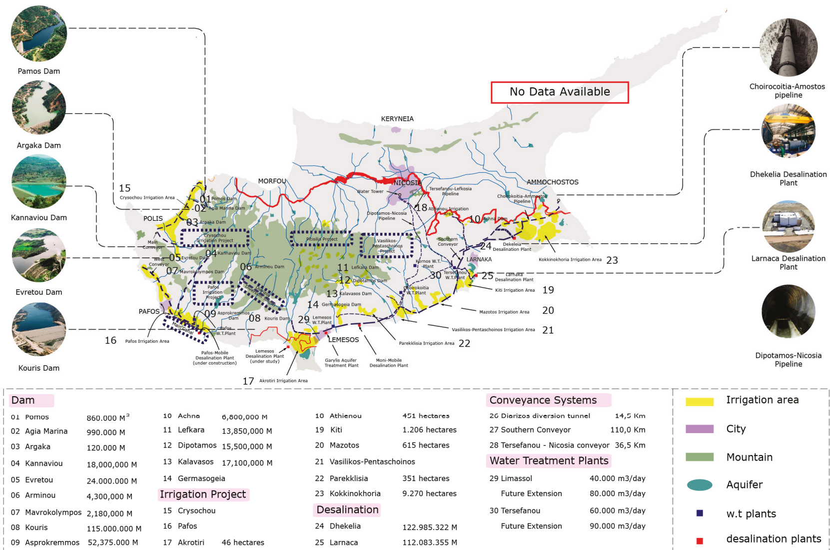


Figure 8. Water works in Southern Cyprus. Source: author's drawing.

3.2.2. Water in Northern Cyprus: Water Pipe from Turkey

In 2012, the Turkish Cypriot government signed an agreement to build an undersea pipeline that would pump fresh water from Turkey to the northern part of the island. The pipeline will bring water from southern Turkey to the small village of Geçitköy in the Turkish Republic of Northern Cyprus. Approximately 25 km of the pipeline will be on land, while 80 km will be under the Mediterranean Sea. Turkey appears to be serious about implementing this project to bring fresh water to Northern Cyprus through an undersea pipeline [43] (see Figure 9). The plans for the water pipeline are that it will supply water to the Turkish Republic of Northern Cyprus only.

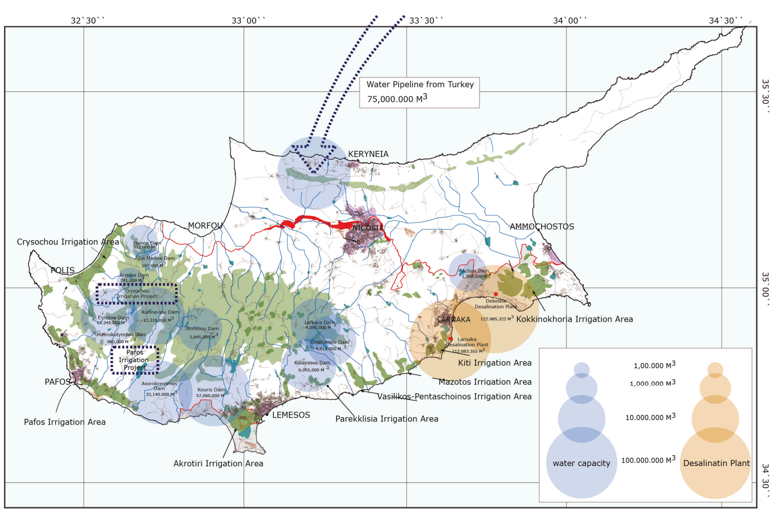


Figure 9. Water consumption in Cyprus. Source: author's drawing.

Water for the pipeline will be supplied by constructing two dams, one in Geçitköy in Northern Cyprus and the other in Alaköprü in southern Turkey. Turkey has previously built dams to store water, and one of these dams, in Allianoi in north-western Turkey, is feared to lead to the flooding of an ancient Roman spa that is still more than 80% non-excavated. Turkey has also constructed a series of dams on the Tigress and Euphrates rivers, which has curtailed the flow of these historical rivers to other countries in the region [32]. Even if successful, the water pipeline project from Turkey to Northern Cyprus will take several years to build, and will necessitate completion of the construction of the dams at Alaköprü and Geçitköy. Connecting the northern part of Cyprus to the Turkish mainland by this water pipeline will emphasize the division of the island into Greek and Turkish sectors, with the result being that the two divisions will work separately rather than together to solve the island's water needs. In addition, Turkey's own water supplies are dwindling, which may reduce the share of its water resources it gives to Northern Cyprus. Thus, having separate water sources for the island may exacerbate the continuing political divisions between Greece and Turkey that have resulted in many serious problems in Cyprus over the years. Further, many Cypriots believe the 77 km undersea pipeline to be laid in very deep water is a fantasy. Moreover, while this solution may work in the short term, it is not a permanent solution, because Turkey itself may not always have sufficient water to supply the Turkish part of the island [43].

3.2.3. Water Ownership

In Cyprus, a water storage tank is installed in almost every household, usually on the roof to provide sufficient water pressure [44]. These tanks have sufficient capacity to store water for at least two days for an average family. Although it is illegal in Cyprus to have additional water storage tanks that run off current water supply, almost every household has more than one of these tanks on its roof. Another problem is that when a water storage tank dries up, people may steal from the tanks of their neighbors.

Until 2001, water supply was restricted in Cyprus, with mains water being switched on only two or three times per week. People learned to keep the mains water in bottles for drinking, and limit their use of washing machines and watering the garden to days when the mains water was on. After a series of particularly dry winters that led to the building of a desalination plant, mains water was on almost constantly, and inevitably people began taking water for granted. Despite bans on hosepipe supply and on-the-spot fines for using hoses, many Cypriots wash their patios or the pavement in front of their homes two or three times per week, with water pouring out of hoses. After two more dry winters, water restrictions were introduced again at the end of March 2008, with mains water on for approximately 12 h of every 48 h. These restrictions eased in January 2010 after one of the wettest winters on record; however, water is still considered a valuable commodity in Cyprus. Mains drainage is slowly being introduced in Cyprus, in line with European regulations, but at present, many houses have septic tanks rather than being connected to the mains for wastewater. In addition to having quarterly water bills, residents have an annual sewerage/drainage bill of approximately EUR60 per person [45]. The strict restrictions on water supply to households mean that people were receiving water for only 36 h per week, reducing independence and freedom [4,46].

Some parts of Northern Cyprus have been experiencing an unprecedented boom in construction and property sales. Turkish settlers in this area enjoy lawns and swimming pools, which require a great deal of water, while some parts of Southern Cyprus survive on as little as 35 L of water per day for their domestic use. What is interesting about this situation is that most of the properties affected by this boom are owned by Greek Cypriots who cannot visit their own houses because of the division of the country.

Here, the following questions should be posed: Who owns water in divided Cyprus? Which group or organization is in charge of controlling water use and plays the key role in maintaining, sustaining, and controlling the water supply?

3.3. Aqueducts and Water Wisdom

During the Persian rule of Cyprus (546–335 BC), Persian *qanats* (underground aqueducts) were imported to the island. The end part of the extensive Persian *qanats* was discovered by archaeologists in the early 1990s in the ancient port of Larnaca (480–300 BC) (see Figure 10a) [47]. This sophisticated water supply system brought sufficient quantities of water from suitable sources outside Larnaca's city walls. Being relatively large and protected within the city's walls, the *qanat* satisfied the needs of Larnaca's population and its busy military and commercial port.

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

Figure 10. Cyprus's aqueducts: (**a**) End part of Persian qanat in the port facilities of ancient Larnaca (480–330 BC); (**b**) Water channel on top of the last and most grandiose series of arches; (**c**) Walled city aqueduct of Nicosia [47,48].

Under Ottoman rule (1571–1878), Larnaca became the main port and most populated center of Cyprus. One of the governors during this rule was Abu Ibrahim (better known as Bekir Pasha) (1746–1748), who constructed an aqueduct for Larnaca (the Bekir Pasha Aqueduct). This 15 km long water supply system, which survives today, comprised a 7 km underground tunnel, made according to the technology used for Persian *qanats*, and 8 km of above-ground arches. The underground tunnel began below the bed of the Tremithos River and ran for 7 km towards the city. Here, the water rose to the surface and flowed for 8 km above ground atop a series of arched aqueducts passing over three small valleys. The water powered two grain mills along the way before reaching Larnaca, where it supplied seven public fountains (only two of which exist today) with running water (see Figure 10c). The three arched constructions, which remain in excellent condition (see Figure 10b), represent an important monument of a collective history of water wisdom.

Built in the eighteenth century, an ancient aqueduct was part of the old water supply system of Nicosia, bringing water from the mountains north of the city. A stone arched construction ran from Kyrenia Gate in the north to Famagusta Gate in the east, supplying water to several fountains in the inner quarters of the city. This section of the aqueduct was known as the Silihtar Aqueduct after the Ottoman governor of the time. During the demolition of a private building [48], 11 arches of this old aqueduct, which were hidden within an adjoining newer structure, were revealed, showing signs of extensive decay. The Nicosia Master Plan project was implemented, which aimed to restore the monument and redesign the surrounding area to include irrigation and drainage systems and improve walkways and passages in the vicinity.

4. Strategy for Cyprus Water Distribution Network

4.1. Transforming Water Management

After declaring the independence of Cyprus in 1960, the Cyprus government placed great importance on water management and securing the adequate provision of high-quality water to inhabitants. The government's main policy, implemented through the Water Development Department, was to increase water supply by constructing dams and conveyance infrastructure under the motto, "No drop of water to the sea" [41]. New measures included the drilling of boreholes and the construction of water treatment plants to supply water for domestic use and irrigation. In addition, the Cyprus government was persuaded to install improved irrigation systems and impose a water charge for domestic and irrigation water. Despite these additional measures, there was still insufficient water supply to meet the increasing water demand, and the decreasing water resources became increasingly evident. Given the lack of surface water runoff in Cyprus, groundwater resources have traditionally provided water for domestic and irrigation use. Thus, the island's aquifers are overexploited, particularly during periods of drought. It is estimated that groundwater resources are heavily over-pumped by approximately 40% of the sustainable extraction level. These issues have resulted in the Cyprus government reorganizing its general water policy in an attempt to ensure that all inhabitants have access to reliable fresh water. Additional measures to ensure a secure water supply have included the use of municipal cleaning waste and tertiary-treated water for groundwater recharge and agriculture, and the introduction of a desalination plant, enabling the government to provide a continuous supply of drinking water to the country. Meanwhile, there have also been extensive efforts to conserve water through public campaigns and education. Further, there have been many revisions made to the current legal and institutional frameworks to structure an environment that will enable efficient water management and the conservation of water-related systems.

In Cyprus, all levels of society—from the national level to the individual level—have authority over water supply. Water systems in Cyprus are separate to some extent; however, they overlap and share the water systems in some instances.

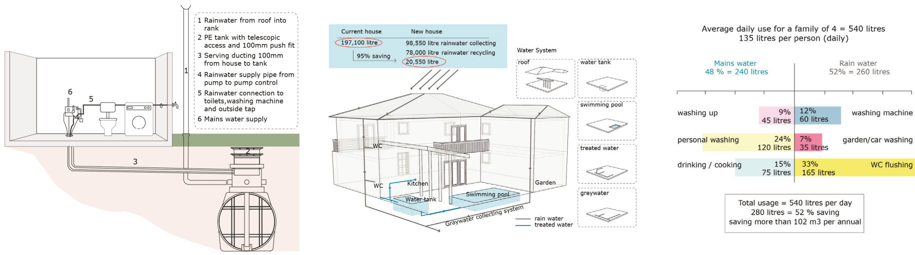
4.2. Strategies for Current Inhabitants

This section provides a vision for a sustainable water supply in Cyprus and strategies that may be adopted by existing households and new inhabitants that use water distribution networks. The section discusses political and social issues from the perspective of their potential to lead to new urbanization in Cyprus.

4.2.1. Strategy 1: Domestic Rainwater Collection

The simplest way to collect water for daily use for existing houses is to install a rainwater tank. Rainwater tanks collect and store rainwater, typically from rooftops via gutters. Such tanks store rainwater for later use, reduce the use of mains water for both economic and environmental reasons, and aid in self-sufficiency. They provide water for drinking, livestock, irrigation, and to refill aquifers when recharging groundwater. Rainwater collected from the roofs of houses and local institutions can make a significant contribution to drinking water availability. Rainwater tanks may involve a high initial installation cost; however, many houses use small-scale tanks to harvest small quantities of water for landscaping or garden use, rather than for potable water [49].

Rainwater falling onto the roof of a dwelling is transported through the downpipes via a filter to an underground rainwater tank located in the rear garden. The rainwater is then pumped into the dwelling and supplies soft water to washing machines and external taps (see Figure 11a). Rainwater tanks also have a mains water supply so that the adequate water can be supplied during dry periods. The average daily water use for a family of four is 540 L. Maximizing the roof surface could harvest 98,550 L or more of rainwater annually (see Figure 11b). Ideally, dwellers should build a system to account for all factors affecting water resource management. By installing a rainwater collection system, each property would improve its water use efficiency and reduce its demand on the public water supply, leading to a 52% water saving (see Figure 11c). This saving is achieved by reducing the requirement for mains water and reducing surface water runoff from dwellings.



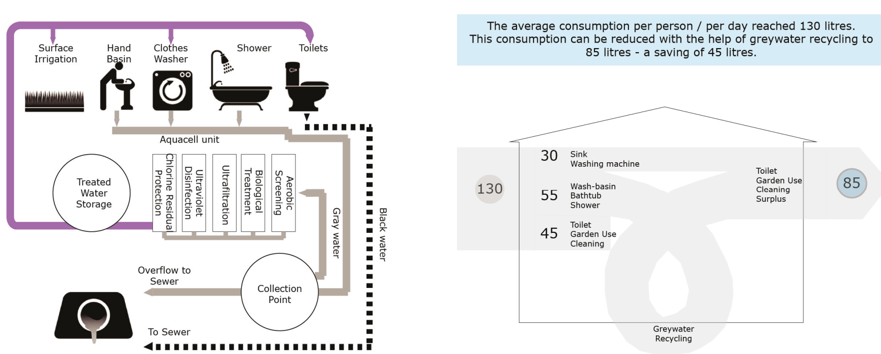
(a) (b) (c)

Figure 11. (**a**) Domestic water supply and discharge; (**b**) Domestic rainwater collection; (**c**) Average daily use for a family of four. Source: revised from [48].

4.2.2. Strategy 2: Recycling of Greywater

Another way to collect water from existing houses is to recycle greywater. Greywater is a means of reducing water consumption primarily by hotels and industries such as laundries. Greywater can be recycled onsite for garden and landscape irrigation, laundering clothes, and toilets. In Cyprus, this type of water reuse is spreading, because its benefits make it an attractive investment for households and organizations. The Cyprus government has established a subsidy program for greywater reuse at the household level [44].

Greywater differs from water from toilets, which contains human waste and is designated as sewage (i.e., blackwater) (see Figure 12a). Greywater has lower pollutant levels than does blackwater, making it easier to treat and recycle [50]. While all greywater contains microorganisms, the health hazards associated with greywater from a multiple-dwelling source are different from those associated with greywater from a single-dwelling source [51]. If collected using a separate plumbing system from blackwater, domestic greywater can be recycled directly within the home, garden, or company and either be used immediately or processed and stored [52].



(a) (b)

Figure 12. (**a**) Recycling of greywater; (**b**) Process of recycling greywater. Source: revised from [50,51].

When greywater is appropriately recycled, it can save approximately 45 L of drinking water per person per day in domestic use. Greywater comprises 50–80% of residential wastewater generated from all sanitation equipment except toilets (see Figure 12b). Therefore, greywater recycling is one of the most useful water solutions for Cypriots.

4.2.3. Strategy 3: New Inhabitants

Apart from water scarcity, it has been demonstrated that the most controversial aspects of water supply in Cyprus are water allocation and control. Thus, a strategy for a water distribution scheme for new inhabitants includes an understanding of the limitations of the Cyprian landscapes and the potential to create a new urbanization regime for Cyprus.

To enable the development of sustainable water distribution systems, new towns on the island should be built with distinct characteristics and spatial quality, while outlying entities should have autonomous water systems. The separation of each town will create "islands within the island" (see Figure 13).

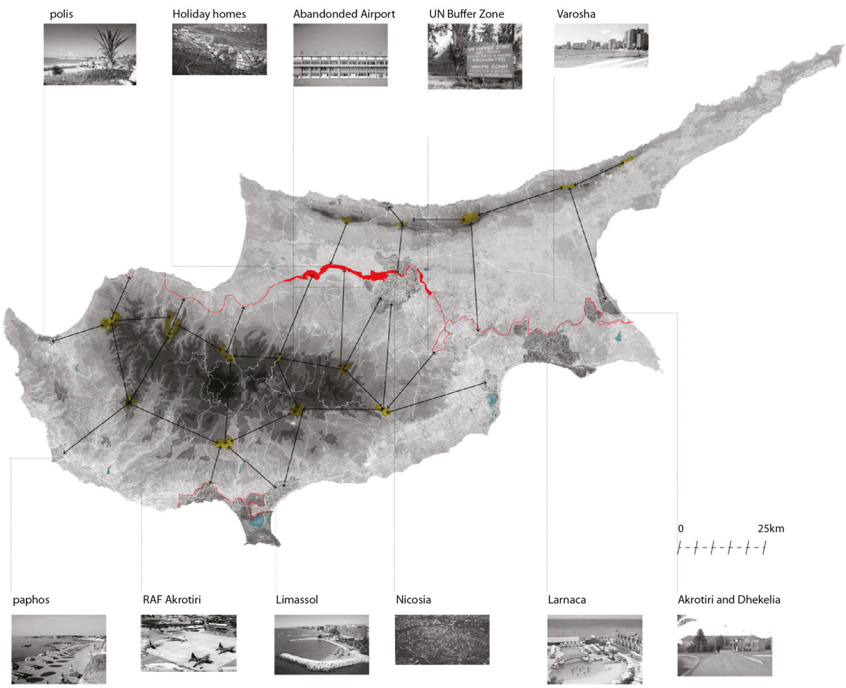
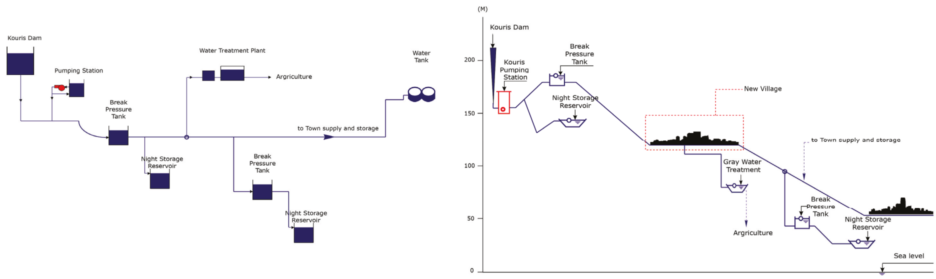


Figure 13. Creating new locations for new islands on the island of Cyprus. Source: author's drawing.

The research involved mapping possible new settlement locations to understand how abstraction and transformation water systems may be used to supply the urban and agricultural needs of new settlement and their inhabitants. The findings of this project demonstrate that urban infrastructure models are appropriate for the natural resources and politics of Cyprus. This strategy is based on the principle that a region's sustainable future depends on creating new autonomous cities, including those on territorial borders, that are organized around a new pattern of land use. Separating towns from each other will creates "islands" within the island of Cyprus. The location of new urban centers requires an understanding of the landscape's limitations and potential. The many years of desertification and water scarcity in Cyprus may be reversed through landscape planning and decentralized systems of water collection, recycling, and abstraction. Figure 14 illustrates how the new water distribution system would work in Cyprus.



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

Figure 14. Water distribution schematic diagram: (**a**) Plan; (**b**) Section. Source: author's drawing.

New inhabitants could also consider combining Strategy 1 (rainwater collection) and Strategy 2 (greywater recycling), which would significantly reduce the cost of separate systems. The average annual precipitation in Cyprus varies from 280 mm in the central plains to 1000 mm at the peak of the Troodos Mountain (with altitude 1950 m), with a mean annual precipitation of 497 mm [4]. Thus, new towns should be located on the hill. The advantage of this is that the greywater would be diluted by rainwater, allowing toilet water to be clear for much of the year.

Figure 15 shows how much water could be collected, used, and stored when the water distribution system presented in Figure 14 is installed for households of two, four, and seven members, respectively. For instance, for a family of two living in a total area of 225 m^2 with a roof surface of 160 m^2, this type of house could collect 132,080 L, comprising 96,000 L from rainfall (roof surface × average rainfall in new urban areas = 160 × 600) and 46,080 L of recycled water, saving 33,530 litter annually. Applying the same calculation, households with four and seven members could save 71,076 L and 225,715 L, respectively.

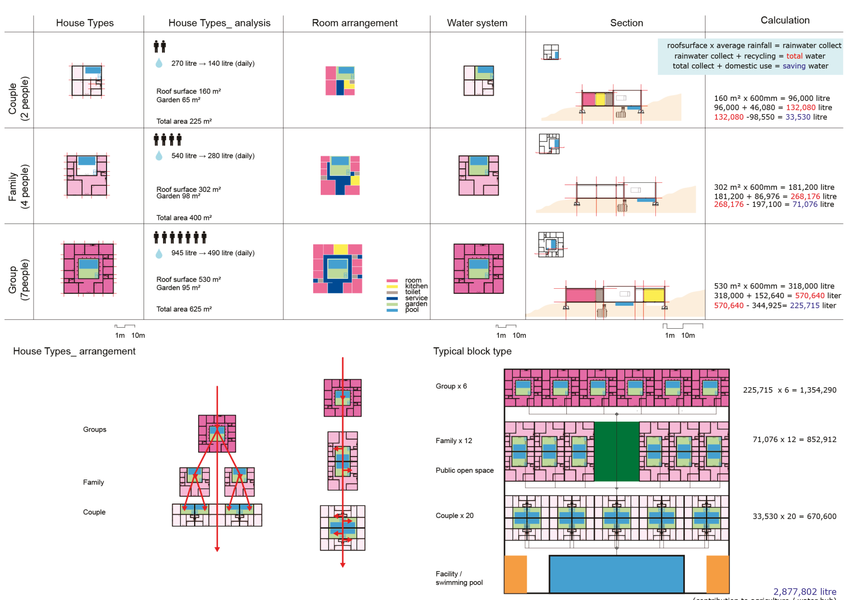
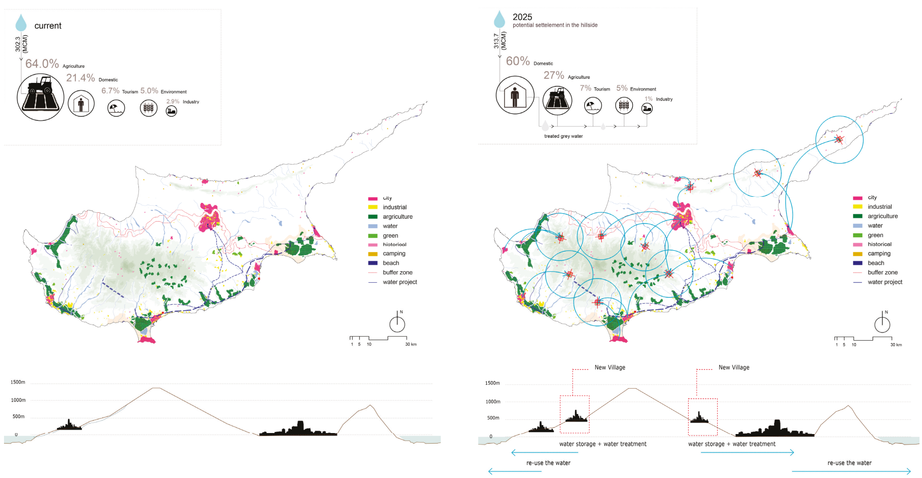


Figure 15. Strategies of water management for new inhabitants. Source: author's drawing.

4.3. Vision of Water Distribution for Sustainable Community

This research has suggested new strategic actions for Cyprus to increase the sustainability of its water management systems. If these new strategic actions are applied to the water distribution networks for existing and new houses in Cyprus, water distribution and management using modern technologies can enable a sustainable water supply based on spatial and temporal changes. Figure 16 represents how much water can be collected, used, and stored in Cyprus if the water transformation strategies presented in Section 4.2 are installed. By appropriately relocating new inhabitants and implementing efficient water infrastructure and architectural planning, water resources are expected to increase from 62.7% to 65% in agriculture and 22% to 24% for domestic use by 2025.



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

Figure 16. Water transformation system for Cyprus: (**a**) Current, (**b**) Vision for 2025. Source: author's drawing.

5. Discussion

As the century continues, increased freshwater resources will be needed in many parts of the world to meet the growing demands of populations and the uncertainties and consequences of climate change. At the same time, more efforts will be required to identify and address the issues that arise, including new threats to the quality of resources and ecosystems, as well as new demands to adjust and mitigate detrimental factors, especially in water stressed regions. This research demonstrates the potential to overcome the gap between water supply and demand using a new approach to water management in Cyprus. It also considers the political conflict in Cyprus in relation to water management. The division of territory on the island has led to conflicts over access to water at different levels of organization. In addition, there are fierce disputes between individuals and organizations over who owns the water. This research found differences in water scarcity issues at the regional and national levels. At the national level, drinking water issues have become increasingly significant for average households in all regions of Cyprus. At the regional level, although transferring water from Turkey to Cyprus may ease local water shortages in Northern Cyprus, it does not completely solve the water supply problems of Cyprus. This study also found moderate-to-high levels of water conflict related to the irrigation networks of desalination plants, which may be avoided through cooperation and the use of modern technology. In addition, areas of Cyprus with fewer water resources are more likely to face greater water conflicts. As discussed, the lack of water supply is one of the most crucial environmental issues in Cyprus. Cyprus has learned to manage drought through experience. A similar crisis in 2008 forced the country to import water on tankers from Greece, a scenario that will not be repeated.

Overall, the main discussion of the research can be summarized as follows: First, choosing advanced technical solutions and practices that improve users' efficiency of water use should support the sustainable, water-saving resources and increasing the quality of water should be the main goal of water management. Second, an increase in the use of alternative water resources is an important option for water conservation, especially in areas already experiencing water scarcity. Rainwater harvesting and storage, particularly desalination for brackish water, also provides a basis for further expansion of water, ensures less competition for water users, and remains a viable alternative in some regions. Last, providing sanitation and safe drinking water to the population should be of high priority, supported by cost-effective and household sanitation systems. The potential impacts of increased demands and climate change on water resources and quality and the variability in quality arising from the spreading pattern of contaminants should be considered and evaluated.

Thus, the recommendations for water management in Cyprus made by this research would improve water management on the island, particularly in adverse climatic conditions. Optimizing water management networks for drought and water shortages requires the use of modern technology to develop new and sustainable methods of water distribution and management. Therefore, this study proposed the following strategies:

- Strategy 1: Transportation of rainwater from the roofs of domestic dwellings through downpipes via a filter to underground tanks located in rear gardens. Rainwater tanks should also have a mains water supply to enable households to receive an adequate water supply during dry periods. This will reduce the need for a mains water supply and reduce surface water runoff from dwellings.
- Strategy 2: Recycling of greywater to meet various water supply needs and reduce the effects of water supply needs on potentially sensitive areas. This will also reduce the volume of pollutants entering rivers and water systems, because less greywater would need to be commercially treated.
- Strategy 3: A new system of water distribution for new inhabitants. New urban areas should be designed with self-sufficient water systems.

6. Conclusions

Water is the most valuable resource in daily life and is greatly important to the political situation in Cyprus. Although Cypriots are obliged to protect and conserve water, the overextraction of groundwater from illegal and uncontrolled abstraction continues, tragically leading to the irreversible depletion of underground aquifers and salinization of coastal aquifers. The rational and sustainable management of water resources is critical for Cyprus to effectively address its water shortages during drought periods. To ensure quality of life for inhabitants and reduce political conflicts related to water supply, it is crucial to redefine water management in Cyprus to ensure a sustainable water supply and avoid extreme water shortages. Cyprus needs to reshape its water management system to be more effective in the future. With respect to minimizing the gap between water supply and demand, solutions for improving supply include increasing reservoirs such as dams and desalination plants, collecting rainwater in tanks for domestic use, and recycling of wastewater, while solutions for reducing demand include education, conservation, and the relocation of new inhabitants.

Thus, this study has achieved its aims by:

- identifying the political and social problems in Cyprus, specifically in relation to water management
- collecting data from previous research to identify the gap between water supply and demand in Cyprus
- extracting and employing the data to reveal interventions for a sustainable water supply in Cyprus through appropriate agrarian planning and efficient architectural planning and construction.

This research found great potential in the use of alternative water sources—rainwater collecting, recycling of wastewater, desalination, and a new water distribution systems as a sustainable strategy for reducing freshwater extractions in water stressed countries. The results of this study may be useful in conceptualizing and recognizing water resource management as a solution to water shortage problems. While water shortages are not a new problem for Cyprus, the island is dealing with serious water disputes and an unequal water distribution because of political conflicts and territorial division. Efficient and visionary water resource management can create a balance between water supply and demand in Cyprus and reduce the effects of the political conflicts. Through citizen participation in water management and the safeguarding of water systems, Cyprus will be better positioned to meet the difficult challenge of supplying all of its inhabitants with sufficient, clean, and reliable water for their domestic and irrigation needs.

Water scarcity is not only a problem for developing countries. This research has focused on Cyprus, which may be considered a microcosm case for managing water scarcity, highlighting potential future problems for cities and regions around world. Using the case study of Cyprus can shed light on alternatives for water supply globally. The vision of architectural and urban design presented for Cyprus represents a new strategy that may be applied in other contexts to improve the sustainability of water management and ensure water demand can be met in water stressed countries in the future.

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sustainability

Article

The Impact of Workplace Disability Facilities on Job Retention Wishes among People with Physical Disabilities in South Korea

Eun Jung Kim [1], Inhan Kim [2] and Mi Jeong Kim [3,*]

[1] Asian Demographic Research Institute, Shanghai University, Shanghai 200444, China; uwcsea0620@hotmail.com
[2] Department of Architecture, Kyung Hee University, Yongin 17104, Korea; ihkim@khu.ac.kr
[3] School of Architecture, Hanyang University, Seoul 04763, Korea
* Correspondence: mijeongkim@hanyang.ac.kr; Tel.: +82-2-2220-1249

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Abstract: The 2030 UN Agenda for Sustainable Development aims to end poverty "in all forms" and achieve sustainable development by 2030, while ensuring that "no one is left behind", including people with disabilities. Disability is referenced eleven times in the Agenda. Disabled people face high risks of poverty because of barriers such as lack of workplace disability facilities. The goal of the study was to examine how workplace disability facilities affect job retention plans among workers with physical disabilities in South Korea and how perceived workplace safety and work satisfaction act as mediators. The 2018 Panel Survey of Employment for the Disabled was used, and we examined 1023 workers with physical disabilities. Path analysis was used to examine the relationships. Results showed that workers whose workplaces provided more disability facilities were significantly more likely to perceive their workplaces as safe and had higher work satisfaction; hence, they were more likely to wish to maintain their present jobs than those whose workplaces offered fewer facilities. However, many workplaces in Korea did not provide any disability facilities. The study provides empirical evidence to support development of policies for improved workplace facilities and work environments for disabled people, in accordance with the UN Agenda.

Keywords: people with physical disabilities; job retention; path analysis; perceived workplace safety; workplace disability facilities; work satisfaction

1. Introduction

In September 2015, the United Nations (UN) General Assembly launched the 2030 Agenda for Sustainable Development, which committed the UN member States to eradicate poverty "in all forms" and achieve sustainable development by 2030, while ensuring that "no one is left behind" [1]. The new Agenda pledged to "endeavor to reach the furthest behind first" [2]. In practice, this means taking explicit action to end extreme poverty, curb inequalities, confront discrimination, and fast-track progress for the furthest behind, including people with disabilities, by setting 17 Sustainable Development Goals (SDGs). Disability is referenced explicitly 11 times in the 2013 Agenda in parts related to education (SDG 4), employment (SDG 8), and inequality (SGD 10) [3]. In 2018, the UN released the first flagship report on disability and sustainability, "Realization of the Sustainable Development Goals by, for and with persons with disabilities" [4]. The report demonstrates that people with disabilities are at a disadvantage with respect to achievement of most Sustainable Development Goals and urges States to ensure full and equal participation of disabled people in society and create enabling environments by, for, and with people with disabilities, in line with the UN Convention on the Rights of Persons with

Disabilities (CRPD). The UN has long identified "accessibility" as a priority in measures promoting equal opportunities for people with disabilities [5].

As a member state of the UN and a state party to the UNCRPD, in 2018, the South Korean (hereafter referred to as Korea) government set 17 goals and 122 targets (i.e., Korea Sustainable Development Goals; KSDGs) in accordance with the 2030 UN SDGs. The 122 targets include increasing fair work opportunities for people with disabilities [6]. Employment is an important means of securing economic stability and buffer against falling into poverty. Yet, in 2019, the employment rate of disabled people in Korea was 34.5%, substantially lower than the national average employment rate of 60.9% [7,8]. Lack of appropriate workplace disability accommodation facilities, such as wheelchair ramps and accessible toilets, makes it difficult for people with disabilities to find and/or maintain work [9].

In Korea, the "Act on the Guarantee of Convenience Promotion of Persons with disabilities, Senior citizens, Pregnant women and Nursing mothers" stipulates building guidelines and rules, including specific details for disability accommodation design features (i.e., doors must have a minimum width of 80 cm, curb height should be below 6–15 cm and must be in a different color from the floor, and wheelchair ramp slopes must have a 4.8-degree angle, etc.) [10]. In 2015, the Korean government revised the Act and announced the "Disability Safety Comprehensive Measure Guidelines" to improve building accessibility for people with disabilities [11]. In the revised Act, from 2015, all public buildings in Korea have been required by law to acquire the Barrier-Free (BF) Environment Certification and from 2018, differential floor-area ratio certification fees are charged based on the BF grades [11]. However, private buildings except for factories larger than 500 m^2 are exempt from these policies [11] and therefore, many workplaces still lack appropriate disability accommodation features and structures in Korea, which prevents disabled people from fully participating in economic activities.

There have been numerous comparison studies of disabled and nondisabled populations and their employment outcomes [12–15]. However, to the best of our knowledge, there have only been two empirical studies on workplace disability facilities and how they affect disabled workers' job decisions and behaviors in Korea. First, Lee and Seo (2014) [9] examined how workplace disability accommodation facilities impact disabled workers' work satisfaction and job retention years (i.e., years worked in the same workplace) and discovered that disabled workers whose workplaces had more accommodating features and structures had significantly higher work satisfaction and thus, worked longer years than those whose workplaces had fewer of these features and structures. They found that work satisfaction had a significant mediating effect between workplace disability accommodations and job retention years. Second, Kim et al. (2014) [16] examined the relationship between workplace accommodation facilities and disabled workers' perceived workplace safety and job retention years. They discovered that disabled workers whose workplaces were more accommodating were significantly more likely to perceive their workplaces as safer, and that these workers were thus more likely to work more years in the same workplaces than those whose workplaces were less or not accommodating.

While both studies are informative, they have two limitations. First, they examined job retention by years worked in the present job. They overlooked the fact that some people who are satisfied with their work environments and whose workplaces provide appropriate disability accommodation facilities may still have shorter periods of job retention because they have recently joined the firms, which undermines the credibility of the study results. Second, both studies examined all disabled workers, including the mentally disabled, for whom accessible building features and structures have less relevance.

The purpose of this study was to address these gaps in the literature. The present study examined how workplace disability accommodation features and structures affect job retention plans (i.e., whether one wishes to maintain the current job in the future) among disabled workers with physical disabilities. We decided to focus on job retention plans because they reflect individuals' voluntary choices and are unaffected by employment start dates. We focus on workers with physical disabilities because workplace disability accommodation features and structures in Korea are geared primarily toward people with physical disabilities. We empirically examined how workplace disability facilities affect disabled workers' job retention plans, and based on Lee and Seo's (2014) [9] and Kim et al.'s (2014) [16] studies, we examined how perceived workplace safety and work satisfaction mediate this relationship using path analysis. Findings from this study provide important insights into understanding workplace disability accommodation features and structures, their impact on employment among disabled people in Korea, and in-built environments for people with disabilities in Korea.

2. Literature Review

Until the 1960s, the traditional approach to disability viewed it as an individual deficit that called for medical assistance and a condition that exempted a disabled person from participating in the labor market. However, after 50 years, a more progressive social model approach was developed, which views disability not as a deficit but rather from a minority identity perspective [17]. It reflected a positive progression towards a "portrait of disabled people as capable and fostered a shift from a conception of disability as an unfavorable condition of inability to enhancement of diversity as a resource in work environments, a conception retained by the Disability Management perspective" [18] (p. 3). In the social model, disability is a consequence of social discrimination, and therefore, the removal of barriers that restrict disabled people from fully integrating into mainstream society is important [17].

Article 27 of the UNCRPD recognizes the rights of people with disabilities to work on an equal basis. State Parties are obligated to safeguard and promote the realization of disabled people's right to work, including providing safe and healthy working conditions (art. 27.1. (b)) and ensuring that reasonable accommodation is provided in the workplace (art. 27.1.(i)) [5].

Disabled workers are at increased risk of occupational injuries [19–21]. They are at greater risk of being injured and they are likely to be more severely injured than nondisabled workers. Therefore, workplace safety is especially important for disabled workers. A key function of workplace disability facilities is to enhance accessibility to work and promote a safe and healthy work environment for disabled workers [22,23]. Numerous studies have examined the impact of workplace disability facilities and work safety and found a positive and significant association between the two variables [24–26]. In Korea, Park et al. (2010) [24] examined the relationship between workplace disability facilities and perceived work safety and found that disabled workers who worked in workplaces that had more disability facilities were more likely to perceive their workplaces as safe than workers with fewer or no facilities. Also, they found that perceived work safety had the most significant influence on work satisfaction among disabled workers. Similar results were also found in Lee and Shin's (2019) [27] study, which used path analysis to examine the relationship between workplace disability facilities, perceived workplace safety, and work satisfaction among disabled workers. They found that individuals who worked in companies that provided more disability facilities were significantly more likely to perceive their workplaces as safe, and therefore, had higher work satisfaction than those who worked in companies that provided fewer disability facilities (i.e., treating perceived workplaces as a mediator).

With regard to workplace disability facilities and job retention, to date, there have only been two studies that have examined the relationship between the two variables in Korea (as mentioned in the introduction). Both studies indicated a significant positive relationship. Kim et al. (2014) [16] included perceived work safety as a mediator and Lee and Seo (2014) [9] included work satisfaction as a mediator in their models. However, perceived work safety and work satisfaction are significantly correlated in Korea as indicated above in Park et al. (2010) [24] and Lee and Shin (2019) [27] studies. As a result, the impact of workplace facilities on job retention is likely to be mediated through not only each individual variable but also by the correlation between the two variables. Hence, in this study, we examined how workplace disability facilities influence disabled workers' job retention plans, including both perceived workplace safety and work satisfaction as mediators in our model. Based on the literature review, we hypothesize that individuals who work in companies that provided more disability facilities are more likely to perceive their workplaces as safer and hence, are more likely to have higher work satisfaction, and therefore, wish to work in their present workplaces (double mediating effect).

3. Methods

3.1. Data

Data for this study were drawn from the 2018 Panel Survey of Employment for the Disabled (PSED) version 2 [28]. The PSED is an annual national survey aimed at examining and addressing the economic activities of the Korean disabled population. The survey consists of demographic-, economic-, and employment-related questions. The initial version of the PSED was first conducted in 2007 and ended in 2015. The second version of PSED was developed in 2016 with a new sample and questionnaire. PSED version 2 uses a multi-stage, stratified clustered random sampling design to survey registered disabled people (i.e., those defined as disabled under the Korean Act on Welfare of Persons with Disabilities and are registered in the welfare system) aged 16 to 65 across the nation. The 2018 PSED surveyed a total of 4104 registered disabled people representative of the national disabled population. In the present study, we decided to use PSED because it is the only nationwide survey that includes diverse information about disabled workers and their workplace environments, including information on disability accommodation facilities.

3.2. Sample

For this study, our analytical sample was wage-earning working people with physical disabilities. We limited disabled workers to wage-earning disabled workers and excluded the self-employed because most self-employed workers have the authority to alter their work environments if they wish to, unlike wage-earners. Also, in this study, we decided to focus on people with physical disabilities because the workplace modification variables in PSED were primarily specific to design changes intended to accommodate physical mobility issues, such as removal of curbs and steps, accessible bathrooms, adequate entrance and doorway space, reserved parking space for the disabled, and suitable pavement for disabled pedestrians. In this study, "physical disabilities" refers to physical conditions that affect a person's mobility, physical capacity, stamina, or dexterity [29]. These can include spinal cord injuries, multiple sclerosis, cerebral palsy, spina bifida, amputation, muscular dystrophy, cardiac conditions, paralysis, polio, stroke, and many other conditions. The Korean Act on Welfare of Persons with Disabilities (art. 2) [30] classifies disability into 15 types and PSED groups them into four categories based on their impairment characteristics: Physical disability, sensory disability, intellectual disability, and internal organ-related disability (i.e., cardiovascular, respiratory, diabetes, etc.). This study selected those who reported having physical disabilities in the PSED, as defined therein. Based on these criteria, for this study, a total sample of 1023 wage-earning disabled workers with physical disabilities was extracted from the 2018 PSED version 2.

As presented in Table 1, on average, workers in our sample were 50 years old and had a monthly salary of KRW 2,210,000 (approximately US $1800), substantially lower than the average Korean wage-earning worker's monthly salary of KRW 2,970,000 (approximately US $2500) [31]. The average number of family members was 2.9 and respondents worked an average of 8 h and 10 min per day. Approximately 18% of the respondents were the head of their household. The majority of the respondents were male (80%), married or in a civil partnership (71%), perceived themselves as middle-class, and reported to have a mild disability (87%). Approximately 54% of respondents worked as non-regular workers, while 47% reported their highest educational attainment as a high school degree, and 83% worked in companies with fewer than 100 employees.

Table 1. Description of the sample (N = 1023).

Characteristics	Mean (SD)
Age	50.47 (9.86)
Monthly salary	2,210,500 (1,377,800)
Household family number	2.87 (1.23)
Work hour per day	8.16 (2.58)
	n (%)
Employment contract type	
Regular	476 (46.5%)
Non-regular	548 (53.6%)
Gender	
Male	813 (79.5%)
Female	209 (20.5%)
Marital Status	
Married or civil partnership	729 (71.3%)
Others	293 (28.7%)
Head of the household	
No	838 (81.9%)
Yes	185 (18.1%)
Self-perceived household economic class	
Low-class	291 (28.4%)
Middle-class	568 (55.5%)
High-class	165 (16.1%)
Education attainment	
Middle school degree or lower	248 (24.2%)
High school degree	479 (46.8%)
College degree or higher	297 (29.0%)
Company size (number of employees)	
10 or less	423 (41.4%)
11–100	423 (41.4%)
More than 100	174 (17.1%)
Disability severity [a]	
Mild disability	892 (87.2%)
Severe disability	131 (12.8%)

Note: Survey weights were applied to represent the population parameters. [a] The PSED defined persons with severe disability as those who meet the criteria for disability classification grades 1, 2, or 3 under the Korean Act on Welfare of Persons with Disabilities and have either brain, sight, mental, heart, respiratory, cerebral palsy, or arm-related physical impairments. All other categories are defined as a mild disability. The present study thus used the PSED definition of disability and did not construct this variable.

3.3. Measures

Workplace disability facility (exogenous variable): The effect of workplace disability accommodation facilities was examined based on the number of disability facilities provided at workplaces. The PSED asked respondents whether each of the following five particular facilities was installed or provided at their workplace: (1) Adequate clear space on pavements for wheelchairs and scooters; (2) reserved parking spaces for disabled people; (3) removal of vertical level changes (e.g., curbs, steps, ruts, gutters, etc.); (4) disability bathrooms; and (5) adequate entrance and doorway space width for wheelchairs. Respondents were asked to report a binary "yes" or "no" outcome. In this study, we summed the facility scores and treated the variable as a count continuous variable ranging 0–5. The Cronbach's alpha test score, which reports how coherent a set of items are as a group, was 0.94, indicating high internal consistency within the five items (relative to a threshold of 0.8).

Perceived workplace safety (mediator): The PSED asked respondents "how safe they feel their workplace is" using a four-point Likert scale (1: very dangerous—4: very safe). In this study, perceived job security was treated as a continuous variable ranging 1–4.

Work satisfaction (mediator): Respondents were asked to rate their overall work satisfaction in the survey on a five-point Likert scale (1: Not satisfied, 5: Very satisfied). Work satisfaction was measured as a continuous variable ranging from 1–5.

Wish to maintain the current job (endogenous variable): The PSED asked respondents "Do you wish to maintain your current job in the future?" Respondents were asked to report a binary "yes" or "no".

Control variables: A range of demographic and work-related factors were controlled. Continuous covariates included are age, average daily work hours, monthly salary, and household size. Employment contract type (non-regular worker vs. regular worker), gender (male vs. female), marital status (married or civil partnership vs. others), head of the household (yes vs. no), and disability severity (mild vs. severe) were measured as binary variables. The PSED defined persons with severe disability as those who meet the criteria for disability classification grades 1, 2, or 3 under the Korean Act on Welfare of Persons with Disabilities and have either brain, sight, mental, heart, respiratory, cerebral palsy, or arm-related physical impairments. All others are classified as having mild disabilities. The present study used the PSED definition to distinguish between severe and mild disabilities. Self-perceived household economic class (low-, middle-, high- class), educational attainment (middle school degree or lower, high school degree, college degree or higher), and company size (10 or less, 11–100, more than 100) were measured as three-category categorical variables in this study.

3.4. Strategy of Analysis

To examine the pathways between workplace disability facilities, perceived workplace safety, work satisfaction, and job retention wishes, we conducted generalized structural equation modeling (GSEM) using STATA 16. GSEM modeling allows researchers to estimate different types of causation simultaneously in a multivariable model, including mediating effects. It also allows examination of simultaneous modeling of several different regression analyses. Unlike the commonly used Ordinary Least Square (OLS) analysis, which can only examine a single relationship between a dependent and an independent variable, the advantage of GSEM is that is it can examine multiple relationships simultaneously, including multiple mediational relationships. This approach aims to examine the underlying mechanisms of a relationship between a dependent and an independent variable through including a third explanatory variable (i.e., mediator) [32]. For example, in our study, we hypothesized that disability facilities (independent variable) affect perceived safety (mediator) and work satisfaction (mediator), and perceived safety and work satisfaction, in turn, affect job retention wishes (dependent variable).

Four different sets of pathway models were examined in this study (see Figure 1). Lee and Shin (2019) [27] found that individuals who worked in companies that provided more disability facilities were significantly more likely to perceive their workplaces as safe and therefore had higher work satisfaction than those who worked in companies that provided fewer disability facilities. That is, perceived workplace safety partially mediated the relationship between disability facilities and work satisfaction (presented in Figure 1 as solid black arrows). Building on Lee and Shin's (2019) study, the present study examined the relationship between disability facilities and job retention wishes, with perceived workplace safety and work satisfaction as mediators. The goal of the present study was to examine whether significant direct effects exist between (1) workplace disability facilities and job retention wishes (disability facilities → job retention wishes), (2) perceived workplace safety and present job retention wishes (perceived workplace safety → job retention wishes), and (3) work satisfaction and job retention wishes (work satisfaction → job retention wishes). Model 1 assumes that direct effects 1, 2, and 3 exist. Model 2 assumes that direct effects 2 and 3 exist. Model 3 assumes that direct effects 1 and 3 exist. Lastly, Model 4 assumes that only direct effect 3 exists. Akaike information criterion (AIC) and Bayesian (or Schwarz) information criterion (BIC) were calculated to compare the fit of different models. AIC and BIC were calculated using the program in STATA 16. AIC and BIC are statistical estimators used to compare different models and find the best model. That is, given a collection of models for the data, AIC and BIC estimate the quality of each model, relative to each of the other models [33]. Smaller AIC and BIC values indicate a better model fit. The AIC and BIC values of each model are presented in Table 3.

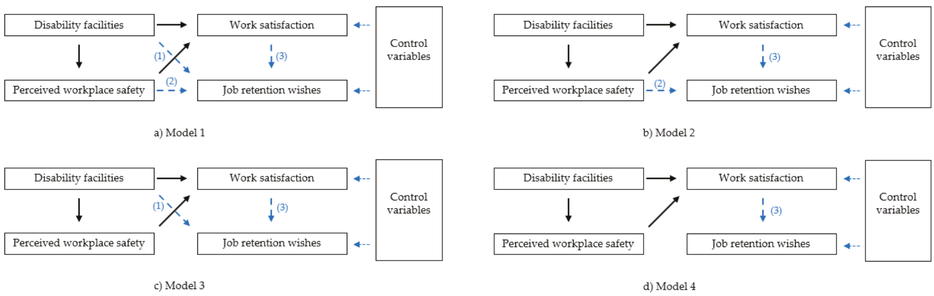

Figure 1. Model comparisons. Building on Lee and Shin's (2019) [27] study (presented as solid black arrows), the present study examined the relationship between disability facilities and job retention wishes, with perceived workplace safety and work satisfaction as mediators (presented as dashed blue arrows). (**a**) Model 1 assumes that direct effects 1, 2, and 3 exist; (**b**) Model 2 assumes that direct effects 2 and 3 exist; (**c**) Model 3 assumes that direct effects 1 and 3 exist; (**d**) Model 4 assumes that only direct effect 3 exists.

4. Results

As presented in Table 2, descriptive results showed that respondents reported an average of 1.7 disability facilities (maximum five facilities) at workplaces. Little more than half (55%) of the respondents reported their workplace did not provide any facilities. The prevalence of each facility was reported as follows: Approximately 33% of respondents reported their workplaces provided suitable pavement for disabled pedestrians (i.e., adequate clear space on pavements for wheelchairs and scooters); 41% reported their workplaces provided reserved parking space for disabled employees; 31% reported their workplaces had removed vertical level changes (e.g., curbs, steps, ruts, gutters, etc.); 30% reported their workplaces had adequate entrance and doorway width for wheelchairs, and 32% reported their workplaces provided accessible bathrooms. Respondents reported an average work satisfaction of 3.5 (out of 5) and perceived workplace safety of 2.8 (out of 4). The vast majority—95% of respondents—reported they wished to maintain their current jobs in the future.

Table 3 presents the generalized structural equation modeling results. First, results showed that respondents who worked in companies that provided more disability facilities perceived their workplace to be significantly safer (b = 0.07, $p < 0.001$; disability facilities → perceived safety) even after controlling for other covariates. Second, respondents whose workplaces provided more disability facilities were significantly more likely to report higher work satisfaction (b = 0.03, $p < 0.01$; disability facilities → work satisfaction) and those who perceived their workplaces were safer were significantly more likely to report higher work satisfaction (b = 0.26, $p < 0.01$; perceived safety → work satisfaction). In total, every additional workplace disability facility had an effect of increasing work satisfaction by 0.05 (i.e., total effect), and this effect was reported to be partially mediated through respondents' perceived workplace safety. Results showed that perceived work safety mediated approximately 40% of the effect between workplace disability facilities and work satisfaction (indirect effect/total effect = 0.02/0.05, $p < 0.001$). Third, results showed that respondents with higher work satisfaction were significantly more likely to wish to maintain their present jobs (b = 1.08, Exp(b) = 2.94, $p < 0.001$; work satisfaction → job retention wishes). On the other hand, the effects of disability facilities on respondents' wish to maintain their present jobs (disability facilities → job retention wishes) and perceived workplace safety on respondents' wish to maintain their present jobs (perceived safety → job retention wishes) were statistically insignificant. The effect of disability facilities on respondents' wish to maintain their present jobs was reported to be fully mediated by perceived workplace safety and work satisfaction. The AIC and BIC results confirmed that model 4, which excludes the pathways "disability facilities → job retention wishes" and "perceived safety → job retention wishes", was the best fit. The final model 4 pathway is depicted in Figure 2.

Table 2. Descriptive results of the main interest variables (N = 1023).

Variables	Mean (SD)
Work satisfaction (1: not satisfied—5: very satisfied)	3.52 (0.61)
Perceived workplace safety (1: very dangerous—4: very safe)	2.78 (0.58)
Number of disability facilities (max 5)	1.63 (2.11)
	n (%)
Job retention wishes	
No	50 (4.9%)
Yes	972 (95.1%)
Number of disability facilities	
0	559 (54.6%)
1	72 (7.0%)
2	56 (5.5%)
3	50 (4.9%)
4	55 (5.4%)
5	232 (22.7%)
Suitable pavement for disabled pedestrians at worksites	
No	683 (66.8%)
Yes	340 (33.2%)
Reserved parking space for disabled people at workplaces	
No	603 (58.9%)
Yes	420 (41.1%)
Removal of vertical changes of levels (curbs, steps, ruts, gutters etc.) at workplaces	
No	702 (68.6%)
Yes	321 (31.4%)
Adequate entrance and doorways space (i.e., width) at workplaces	
No	718 (70.2%)
Yes	305 (29.8%)
Disability bathroom at workplaces	
No	696 (68.0%)
Yes	327 (32.0%)

Notes: Survey weights were applied to represent the population parameter.

Table 3. Generalized Structural Equation Modeling (GSEM) results.

	Model 1	**Model 2**	**Model 3**	**Model 4**
	Coef. (SE)	**Coef. (SE)**	**Coef. (SE)**	**Coef. (SE)**
Perceived safety ← Facilities	0.07 (0.01) ***	0.07 (0.01) ***	0.07 (0.01) ***	0.07 (0.01) ***
Work satisfaction ← Facilities	0.03 (0.01) **	0.03 (0.01) **	0.03 (0.01) **	0.03 (0.01) **
Work satisfaction ← Perceived safety	0.26 (0.03) ***	0.26 (0.03) ***	0.26 (0.03) ***	0.26 (0.03) ***
Job retention wishes ← Work satisfaction	1.00 (0.24) ***	1.02 (0.24) ***	1.04 (0.24) ***	1.08 (0.23) ***
Job retention wishes ← Facilities	0.08 (0.08)	-	0.09 (0.08)	-
Job retention wishes ← Perceived safety	0.21 (0.25)	0.25 (0.25)	-	-
Job retention wishes ← Regular worker	−0.10 (0.32)	−0.10 (0.32)	−0.07 (0.32)	−0.07 (0.32)
Job retention wishes ← Age	0.02 (0.02)	0.01 (0.02)	0.01 (0.02)	0.01 (0.02)
Job retention wishes ← Education attainment				

Table 3. *Cont.*

	Model 1	Model 2	Model 3	Model 4
	Coef. (SE)	**Coef. (SE)**	**Coef. (SE)**	**Coef. (SE)**
(reference: *Middle school degree or lower*)	−0.04 (0.41)	−0.04 (0.41)	−0.05 (0.42)	−0.05 (0.41)
High school degree	0.02 (0.49)	0.06 (0.48)	0.04 (0.48)	0.08 (0.48)
College degree or higher				
Job retention wishes ← Company size				
(reference: *10 or less*)				
11–100	−0.22 (0.32)	−0.16 (0.31)	−0.22 (0.32)	−0.16 (0.31)
More than 100	−0.17 (0.40)	−0.06 (0.39)	−0.18 (0.40)	−0.05 (0.29)
Job retention wishes ← Subjective household class				
(reference: *low*)	−0.37 (0.34)	−0.34 (0.34)	−0.35 (0.34)	−0.31 (0.33)
Middle class	−0.85 (0.48)	−0.80 (0.48)	−0.84 (0.48)	−0.78 (0.48)
High class				
Job retention wishes ← Severe disability	0.31 (0.46)	0.23 (0.45)	0.32 (0.45)	0.24 (0.45)
Job retention wishes ← Logged salary	0.48 (0.29)	0.47 (0.29)	0.46 (0.30)	0.45 (0.29)
Job retention wishes ← Married or civil-partnership	−0.12 (0.36)	−0.12 (0.36)	−0.12 (0.36)	−0.12 (0.36)
Job retention wishes ← Household family size	0.09 (0.14)	0.08 (0.14)	0.09 (0.14)	0.07 (0.14)
Job retention wishes ← Household head	0.89 (0.46)	0.91 (0.46) *	0.90 (0.45)	0.93 (0.46) *
Job retention wishes ← Work hour	0.10 (0.07)	0.09 (0.07)	0.09 (0.07)	0.08 (0.07)
Job retention wishes ← Female	−0.72 (0.40)	−0.71 (0.40)	−0.68 (0.40)	−0.66 (0.40)
variance (e. perceived safety)	0.31 (0.01)	0.31 (0.01)	0.31(0.01)	0.31 (0.01)
variance (e. work satisfaction)	0.29 (0.01)	0.29 (0.01)	0.29 (0.01)	0.20 (0.01)
AIC	3830.35	3829.47	3829.05	3828.41
BIC	4032.50	4026.69	4026.27	4020.70

Note: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

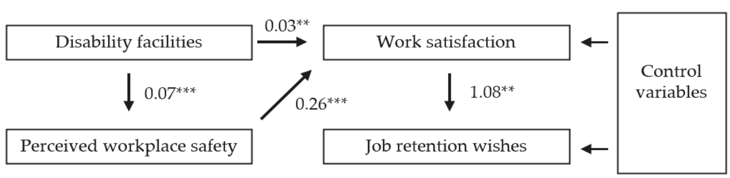

Figure 2. Parameter estimates based on Model 4. For simplicity, nonsignificant paths and error variance estimates are not shown. ** $p < 0.01$, *** $p < 0.001$

5. Discussion and Conclusion

The present study examined the relationships between workplace disability accommodation features and structures, perceived workplace safety, work satisfaction, and job retention wishes among disabled workers with physical disabilities using path analysis. Pathway analysis showed that those whose workplaces provided more disability facilities were significantly more likely to perceive their workplaces to be safe and have higher work satisfaction, and hence, they were more likely to wish to maintain their present jobs in the future even after controlling for other individual and work factors, corroborating our hypothesis.

Before discussing the implications of this study, it is also important to consider the limitations of the study and directions for future study. First, the present study measured the impact of workplace disability facilities by the number of available facilities. Yet, it is unclear if having multiple facilities is always more beneficial. One or two particular facilities may have more impact than others on an individual's work retention decisions. However, with the limited information available, it is difficult to discern which facilities have a bigger impact on disabled workers' retention decisions. Hence, based on previous literature [9,10,16,24,27], the present study also measured disability facilities by the number of available facilities. Future studies are needed that examine the relative influence and importance of disability facilities on disabled workers and their retention decisions. Second, the present study examined job retention wishes and not actual job retention rates due to data limitation. However, considering that some employees may have to leave their jobs involuntarily, for example, for reasons related to economic recession, even if they are satisfied with their work environment, we believe job retention wishes to be a more accurate barometer of disabled people's voluntary employment decisions than actual job retention rates. Lastly, the present study examined environmental building disability accommodations. Workplace disability accommodations not only include environmental building design changes but also work adjustments (i.e., reduced and flexible work hours, job restructurings such as reduced manual tasks, job coaches, and training) and provision of equipment and devices such as computers with voice recognition. Due to data limitations, we could not examine non-physical work adjustments. However, most non-physical adjustments have less relevance to perceived workplace safety than physical adjustments. In this study, we were interested in how perceived workplace safety affects future retention plans. Thus, we decided to focus on environmental building structures and features.

Despite these limitations, the study makes several important contributions. The present study is the first to empirically examine how workplace disability facilities influence disabled workers' job retention decisions on a national scale in Korea. Also, using pathway analysis, the present study is the first to examine how perceived workplace safety and work satisfaction mediated this relationship. Several implications can be drawn from this study.

First, study results showed that the majority of respondents reported that their workplaces did not provide disability facilities. Only 30% of respondents reported their workplaces had adequate entrance and doorways for wheelchair accessibility, and 32% reported their workplaces had disability bathrooms. Approximately 41% of respondents reported their workplaces provided reserved parking spaces for disabled employees and 31% reported their workplaces removed vertical changes of levels for easy access. The "Act on the Guarantee of Convenience Promotion of Persons with disabilities, Senior citizens, Pregnant women and Nursing mothers" stipulates that all public buildings and facilities, as well as factories with a total floor area larger than 500 m^2, are mandated to install disability-accommodating facilities. However, according to a 2017 survey report [9], only 25% of disabled workers were reported as factory workers, and the majority were reported as either service and sales workers or office workers; as a result, their workplaces were not obligated to provide disability facilities as mandated under the Act. Also, among disabled factory workers, approximately 30% worked in companies with fewer than 10 employees; hence, their workplaces are likely to be less than 500 m^2 [9]. In the UK, under the Equality Act 2010, all employers, regardless of company size or industry are obligated to make reasonable adjustments to accommodate disabled employees [34]. The government "Access to Work" grant helps fund the adjustments [35], which lightens the burden on employers that employ the disabled and make the adjustments. As a result, according to a 2009/10 UK survey, which examined the socioeconomic experiences of disabled population in the UK, only 4% of disabled respondents reported that lack of disability facilities and difficulties accessing buildings were barriers to employment [36]. Likewise, Australia has a similar program, the Employment Assistance Fund (EAF), to cover the cost of making workplace changes [37]. The Korean government should consider revising the law to include more private workplace buildings for which disability facilities are mandated and also consider developing a public grant, which funds the cost of modifications. Currently, in Korea, responsibility for making modifications falls entirely on the employer.

Second, results showed that the relationship between workplace disability facility and job retention wishes were fully mediated through perceived workplace safety and work satisfaction, and no significant direct effect existed between disability facilities and job retention wishes (disability facilities → job retention wishes). If we ran an OLS analysis, instead of a path analysis, between workplace disability facility and job retention wishes, the effect of workplace disability facility on job retention wishes would have been insignificant, providing an inaccurate picture of the dynamic. By using path analysis, we proved that there is a positive relationship between workplace disability facility and job retention, and that it is fully mediated by perceived work safety and work satisfaction. Based on our findings, we know workers whose companies provided more disability facilities were significantly more likely to perceive their workplaces as safer and hence, are more likely to have higher work satisfaction, and therefore, more likely to stay at their present jobs. Such findings provide incentives to policymakers and employers to implement better workplace disability facilities and related policies.

Third, it is important to note that the majority of 95% of respondents reported that they wished to maintain their current jobs in the future (see Table 2), which may be due to the high unemployment rate among disabled population. This may also be a reason behind the no direct effect between disability facilities and job retention wishes. The majority of workers are likely to wish to maintain their current jobs regardless of workplace disability facilities because of the high level of unemployment among disabled population, and the relationship between job retention wishes and disability facilities becomes significant only when factors such as work satisfaction and perceived work safety are also taken into consideration.

The 2030 Agenda for Sustainability Development, which was adopted by all UN member states in 2015, pledged to end poverty in all forms and ensure "no one is left behind". Disabled people face an increased risk of poverty due to barriers to paid work. Making workplaces more accessible is important to securing disabled people's economic stability and independence. Our study findings indicate that Korea still has much progress to make in this area. Despite our findings that disability facilities help increase disabled workers' perceived safety, work satisfaction, and job retention, more than half of the respondent disabled workers indicated that their workplaces did not provide any disability facilities. The authors urge the development of policies that better address workplace disability facilities and accessibility for the disabled.

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Effects of a Yoga Program in Reducing Cardiovascular Disease Risk Factors in Workers of Small Workplaces: A Pilot Test

Won Ju Hwang [1], Jin Ah Kim [2,*] and Ji Sun Ha [1]

[1] College of Nursing Science, Kyung Hee University, Seoul 02447, Korea; hwangwj@khu.ac.kr (W.J.H.); hajs@khu.ac.kr (J.S.H.)

[2] Department of Nursing, Gyeongju University, Gyeongju 38065, Korea

* Correspondence: kimja@gu.ac.kr; Tel.: +82-2-961-0852

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Abstract: The purpose of this study was to evaluate the effects of a yoga program provided to workers in small businesses to reduce cardiovascular disease (CVD) risk factors. A nonequivalent control group pre/post-test design was used. The experimental group (n = 31) was assigned a yoga program consisting of yoga postures designed for meditation, strengthening, stretching, and balancing, given twice weekly for 12 weeks. The control group (n = 38) was given no other intervention. The mean age was 48.1 years old in the experimental group and 47.7 years old in the control group. Three trained investigators collected the questionnaires and one month after completing the 12-week yoga program, the same questionnaires that were administered at baseline were again administered. Psychosocial variables (depressive symptoms and job stress), health promotion behaviors, and body measurements (weight and waist circumference) were measured for the program evaluation. The yoga program was effective in improving waist circumference (from 81.8 to 79.2, $p < 0.001$) and diastolic blood pressure (from 81.0 to 79.1, $p = 0.004$) as compared to the control group. Furthermore, the experimental group's job stress score decreased from 1.38 to 1.02, but it was not statistically significant ($p = 0.240$). A yoga program could be a useful intervention for workers with CVD risk factors, but it was not effective in psychological factors such as job stress and depression. A long-term intervention approach is important to confirm the psychosocial effect. Therefore, future research is needed to investigate the long-term outcomes of such interventions.

Keywords: blue-collar workers; intervention study; health promotion; cardiovascular disease

1. Introduction

As of 2018, the number of small enterprises in Korea reached 2,649,967, accounting for 99.8% of all enterprises, and the number of workers in small enterprises accounted for 83.0% (15,818,937) of the entire worker pool [1]. Furthermore, the industrial accident rate in small enterprises is 0.60%, which is higher than the rate of 0.24% in medium-sized or larger enterprises with more than 300 workers [1]. The most prevalent problem among workers is conditions related to physically burdening work (32.3%), followed by lower back pain (31.9%), pneumoconiosis (9.7%), and cardiovascular disease (CVD; 6.8%). Statistics data showed that CVD (39%) was the second cause of mortality for work-related accident death in 2013, but it became the first cause among them in 2018 [1]. According to many previous studies [2–4], workers in small workplaces are at high risk of developing cardiovascular disease due to various occupational environmental factors. Firstly, workers in small workplaces suffer from physical fatigue caused by increased physical labor due to incessant physical work and lack of human resources. Moreover, lack of human resources leads to overtime work. For this reason, workers have irregular lifestyles such as late-night meals, poor sleep quality, lack of sleeping time, and lack of exercise [3]. Secondly, workers have a low level of knowledge and risk perceptions for the CVD diseases in small-sized workplaces [3], because of lower educational level and increased age compared with workers in medium- and large-sized workplaces [4]. Thirdly, employers are inclined to pursue company profits over workers' health because of economic difficulties in small-sized workplaces [3]. Finally, despite the vast pool of workers in small enterprises and lots of CVD risk factors in small-sized workplaces, workers' health is currently not managed systematically due to a lack of on-site health managers, which has led to poor health behavior and health status among workers [2]. Therefore, intervention studies to reduce CVD risk factors for workers in small-sized workplaces are needed. Nowadays, research to reduce the risk of CVD among workers in small workplaces is constantly being studied [5,6]. Also, psychosocial factors such as job stress and depression are considered as CVD risk factors [6]. In particular, job stress, a factor found to have an impact on CVD in workers, refers to "the physical and emotional response in workers when their competence, resources, and needs fall short of the work requirements" [7]. Job stress has emerged as a common occupational health problem second only to musculoskeletal diseases. Job stress is a key risk factor that not only induces CVD [8–14], but also contributes to financial loss and reduced productivity as a result of disasters and accidents, which can undermine the competitiveness of local communities as well as the nation. For this reason, job stress is acknowledged as a factor that threatens the development and health of business owners, local communities, and the nation [15]. The Occupational Safety and Health Research Institute (OSHRI) investigated working environments of a sample of Korean workers, and reported that 18.4% and 15.1% of male and female workers, respectively, experience job-related stress [16]. Approximately 95.7% of workers of small enterprises were found to have diseases caused by overtime work and stress [1]. These findings highlight the need of interventions focused on psychosocial aspects to prevent occupational diseases in small enterprises.

Yoga is empirical evidence of the mechanism for reducing stress; three mental mechanisms such as positive affect, mindfulness, and self-compassion and biological mechanisms (posterior hypothalamus, interlecukin-6, c-reactive protein, and cortisol) are presented in the positive effect. The suppression of the hypothalamus and cortisol was confirmed in the relationship between yoga and stress [17,18]. Furthermore, yoga is a type of exercise that corrects imbalances of the body and mind, and facilitates the recovery of humans' innate capacity to maintain balance [19]. The exercise involves practicing physical postures that stabilize the mind, and it relieves depression or physical stress by improving flexibility, facilitating the flow of physical energy, and improving physical functions, such as visceral functions, thereby promoting health [20,21]. Yoga has been found to have diverse physical and emotional effects, including enhancing pulmonary functions, reducing oxygen consumption, regulating blood pressure, reducing cardiovascular risk factors, and reducing pain and anxiety [21–24]. Yoga encompasses complementary and integrative therapy approaches with verified efficacy and stability [25], and it involves easy and physically non-burdening motions, both of which render it an appropriate type of exercise to prevent CVD in workers of small enterprises.

In previous studies, when applied to various participants from children to the elderly [22–25], yoga has been reported to reduce anxiety and depression in hospitalized patients with mental health disorders [22], reduce middle-aged women's stress, cortisol, glucose, resting heart rate, diastolic blood pressure, and mean arterial blood pressure [23], reduce fatigue, pain, stress, and anxiety in patients with multiple sclerosis [24], reduce autonomic nerves, salivary cortisol, immunoglobulin A, and stress index in elementary school students [26], and reduce blood pressure and cholesterol in the elderly with essential hypertension [27]. Meanwhile, studies that have tested the effects of yoga on workers found that yoga lowers job stress, psychological stress, and anxiety in office workers [28], lowers stress responses in professional workers [29], improves physical functions and pain in menopausal female workers [30], promotes weight loss in wellness center workers, lowers diastolic blood pressure, improves range of motion, decreases body fat, and improves quality of life [31]. However, there has been no study that investigated the effects of yoga in reducing CVD risks including psychological factors in workers of small enterprises. The purpose of this study was to investigate the effects of a yoga program to reduce CVD risk factors including psychological factors such as job stress and depression provided to workers in small enterprises.

The study examined the effects of a yoga program provided to workers in small businesses to reduce cardiovascular disease (CVD) risk factors, including psychological health behavior factors, and physical measurements.

2. Materials and Methods

2.1. Study Population

This was a quasi-experimental study with control groups different in number of participants and pre/post-test design that aimed to examine the efficacy of a yoga program in reducing CVD risk factors in workers in small enterprises who have CVD risks. The CVD risk groups were determined based on the CVD risk assessment criteria established by the Korea Occupational Safety and Health Agency (KOSHA) based on the 2003 WHO International Society of Hypertension guidelines (WHO-ISH) (① ≥SBP 140 mmHg or ≥DBP 90 mmHg, ② age (≥55 years in men, ≥65 years in women), ③ current smoking, ④ high cholesterol ≥240 mg/dL, ⑤ early occurrence of CVDs in family members in a direct line (<50 years), ⑥ obesity (≥body mass index 30 kg/m^2), physical inactivity, ⑦ atrial fibrillation) [32]. The participants in the experimental group have had one or more of the above risk factors. Sixty-nine workers in small enterprises based in S and Y city who provided informed consent were enrolled. The experimental group comprised 31 workers of a small audio equipment components manufacturing enterprise located in S city, and the control group comprised 38 workers of three small enterprises which manufactures copper fittings located in Y city, all of which are geographically distant from the experimental group (Control group 1: n = 11, Control group 2: n = 15, Control group 3: n = 12).

Sample size was determined using the G*Power 3.1 program. Based on a test of the means of the two groups, 52 people (26 for each group) were estimated to be required to attain significance $\alpha = 0.05$, with effect size d = 0.08 and power $(1 - \beta) = 0.80$. The effect size was estimated based on the study by Oh and Lee [29], which examined the effects of a yoga program on workers' stress.

Thirty-three participants were selected for the experimental group, and 41 participants who provided informed consents were selected for the control group, in consideration of possible dropouts. After excluding two participants from the experimental group for having a program participation rate of below 80% and three participants from the control group for leaving too many omissions in the questionnaire, a total of 31 and 38 participants from the experimental and control groups, respectively, were included in the final analysis. This study was conducted for six months from March to September 2015.

2.2. Experimental Design

2.2.1. Development of a Yoga Program

The yoga program was developed based on a systematic literature review performed by one nursing professor and two researchers about interventions that lower CVD in workers, with cooperation from a professional yoga instructor.

Figure 1 shows a flow chart of the yoga program intervention procedure. It provides the contents of the yoga program which was structured in three stages: warm-up, yoga poses, and cool-down through breathing and meditation. The first stage, the warm-up, comprised yoga breathing (one minute), meditation (two minutes), and simple stretching exercises (two minutes) for a total of five minutes. The second stage, the yoga pose stage, was designed to proceed for 20 min. During this stage, 11 yoga poses (sun salutation, triangle, cobra, grasshopper, alligator, chair, fish, kneeling, cat, spinal twist, extended puppy) were performed to relax the mind, strengthen muscles, and increase flexibility and balance. The third stage, the cool-down stage, comprised two minutes of yoga breathing and three minutes of meditation to focus the mind on oneself, to promote relaxation and reduce stress (Figure 1).

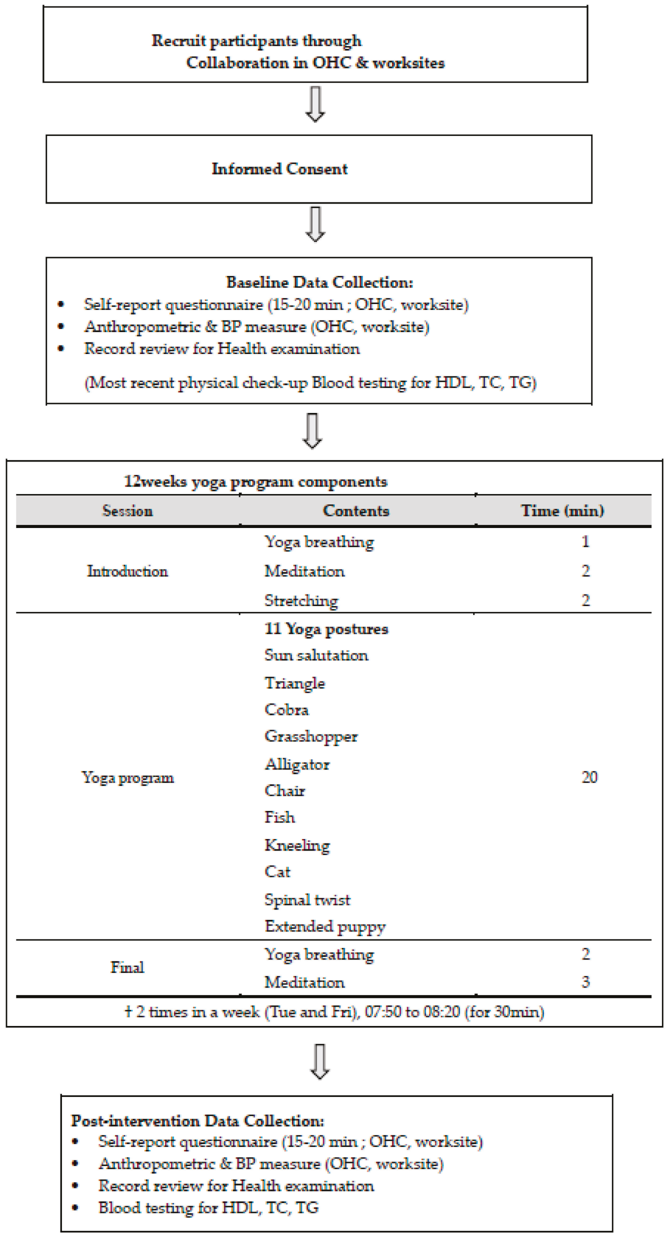

Figure 1. Flow chart of yoga program intervention procedure, OHC = occupational health center; BP = blood pressure; TG = triglycerides; TC = total cholesterol; HDL = high-density lipoprotein.

2.2.2. Baseline Measurement in Experimental and Control Groups

Prior to beginning the study, researchers selected experimental and control groups. Then, the investigator individually met with the owner or health manager of each small enterprise to obtain informed consent and request cooperation. Three trained investigators visited each enterprise in March 2015 to administer the questionnaires. The investigators explained to the workers about study aims, confidentiality, the use of collected data strictly for study purposes, and the contents of the yoga program, and obtained signed consent forms.

Structured questionnaires were administered only to those who provided informed consent to investigate workers' depressive symptoms, job stress, and health-promoting behaviors. It took about 15–20 min for each participant to complete the questionnaires. Height and weight were measured using an electronic measuring scale, and the body mass index (BMI) was computed. Waist circumference was measured around the ilium using a measuring tape. Blood pressure was measured using a manual sphygmomanometer after a 15-min resting period.

2.2.3. Experimental Treatment: Yoga Program

The yoga program, intended to lower job stress and CVD risks, was administered by a professional yoga instructor twice a week for 12 weeks (24 sessions) from 28 April 2015 to 26 August 2015. Each session was performed for 30 min, from 7:50 a.m. to 8:20 a.m., before work start. Yoga took place in a large auditorium, and no dropouts occurred during the 12-week yoga program. In contrast to the yoga group, the participants in the control groups were simply instructed to maintain their normal life without participating in regular physical activity programs.

2.2.4. Post-Intervention Measurement in Experimental and Control Groups

On 21 September 2015 (one month after completing the 12-week yoga program), the same questionnaires that were administered and the weight, waist circumference, and blood pressure that were measured at baseline were again administered and measured for both the experimental and control groups.

2.3. Ethical Considerations

This study was approved by the Institutional Review Board of K University Hospital (IRB No. KMC IRB 1443-06). Prior to recruiting the participants, the investigators visited the enterprises of interest to obtain informed consent and request cooperation from the owner and health managers. Before beginning the program, signed informed consent was obtained from all participants. The consent form included a description and contact information for the investigator, aims and method of the study, and statements noting that personal information would not be exposed and that the participants could withdraw at will at any point in the study. Anonymity of the collected data was ensured by using individualized allocation numbers (ANs), and all collected data were stored in a locked safe. A small gift was given to both the experimental and control groups for participating in the study after the study was completed, and a leaflet describing methods to reduce job stress and prevent and manage CVD was also provided to the control group at no cost after the study was concluded.

2.4. Measurements

2.4.1. Depressive Symptoms

Depressive symptoms were measured with the Korean version of the Center for Epidemiologic Studies Depression (CES-D) Scale, which was originally developed by Radloff [33] and translated and validated by Cho and Kim [34]. A higher score reflects more severe depressive symptoms. The reliability (Cronbach's α) of the Korean version of the CES-D was high (0.90) at the time of the development, but the Cronbach's α of the scale in this study was 0.67 at baseline, and 0.72 at post-intervention.

2.4.2. Job Stress

Job stress was measured using the Korean version of Effort–Reward Imbalance (ERI), which was originally developed by Siegrist et al. [35] and adapted by Eum et al. [36]. The questionnaire is based on the effort–reward imbalance model and consists of 17 items (6 items on effort and 11 items on reward). Each item is rated on a five-point scale from 1 to 5. Job stress is assessed using the ER ratio, obtained by dividing the total effort score by the total reward score. Specifically, the ER ratio is calculated by first adjusting the total reward score with a correction factor, 6/11 (=0.545) to transform the total scores of effort and reward to 1 (as there are 6 and 11 items in each of the subscales, respectively), and by computing the ratio with the transformed reward score as the denominator and the effort score as the numerator. An ER ratio less than 1 indicated low-level job stress, and an ER ratio greater than 1 indicated the presence of high-level job stress. The reliability (Cronbach's α) of the scale in previous studies [35,37] was 0.68 and 0.71, respectively, and that in this study was 0.90 at baseline point and 0.76 at post-intervention.

2.4.3. Health-Promoting Behaviors

Health-promoting behaviors were measured using the Health Promoting Lifestyle Profile II (HPLP II) developed by Walker, Shechrist, and Pender [38] and adapted by Hwang [39]. Each item is rated on a four-point scale: 1 for "not at all", 2 for "sometimes", 3 for "frequently", and 4 for "regularly." The HPLP II consists of 52 items, and the higher the score, the higher the level of health-promoting behavior. The reliability (Cronbach's α) of the overall scale at the time of the development was 0.94. The Cronbach's α values in the present study at baseline (post-intervention) was 0.93 (0.88).

2.5. Data Analysis

The data were analyzed as follows, using SPSS/WIN 22.0 software.

First, the participants' general and disease-related characteristics were analyzed, with results reported as mean and standard deviation or number and percent.

Second, the homogeneity of general characteristics between the experimental and control groups was analyzed with Chi-square tests and F-tests.

Third, the effects of the yoga program intended to reduce the CVD risk factors in workers of small enterprises were assessed using two-way repeated measure ANOVA.

3. Results

3.1. Homogeneity Testing

A total of 69 participants were enrolled, with 31 in the experimental group and 38 in the control group. There were no significant differences between the two groups in gender ($p = 0.354$), educational level ($p = 0.235$), marital status ($p = 0.437$), monthly income ($p = 0.601$), daily working hours ($p = 0.707$), or age ($p = 0.845$), confirming homogeneity between experimental group and control group (Table 1).

Table 1. Homogeneity Test for General Characteristics between Experimental and Control Groups (N = 69).

Characteristics	Categories	† Exp. (n = 31)	‡ Cont. (n = 38) n (%)/Mean ± SD				χ^2 or F	*p*
		n (%)/Mean ± SD	Group 1 (n = 11)	Group 2 (n = 15)	Group 3 (n = 12)	Total (n = 38)		
Sex	Male	14(45.2)	6(54.5)	6(40.0)	8(66.7)	20(52.6)	0.38	0.354
	Female	17(54.8)	5(45.5)	9(60.0)	4(11.6)	18(47.4)		
Educational level	≤Middle school	3(9.7)	0(0.0)	1(6.7)	2(16.7)	3(7.9)	2.89	0.235
	High school	23(74.2)	6(54.5)	8(53.3)	8(66.7)	22(57.9)		
	≥College	5(16.1)	5(45.5)	6(40.0)	2(16.7)	13(34.1)		
Marital status	Unmarried	8(25.8)	5(45.5)	5(33.3)	4(33.3)	14(36.8)	0.96	0.437
	Married	23(74.2)	6(54.5)	10(66.7)	8(66.7)	24(63.2)		
Monthly income (10.000 won)	≤100	1(3.2)	0(0.0)	0(0.0)	0(0.0)	0(0.0)	1.87	0.601
	100~200	13(41.9)	7(63.6)	1(6.7)	5(41.7)	13(34.2)		
	201~300	7(22.6)	2(18.2)	5(33.3)	4(33.3)	11(28.9)		
	≥301	10(3203)	2(18.2)	9(60.0)	3(25.0)	14(36.8)		
Working hours (/day)		55.56 ± 4.71	55.45 ± 4.72	54.87 ± 5.23	55.00 ± 5.22)	55.08 ± 4.96	0.38	0.707
Age (years)		48.15 ± 8.26	49.46 ± 6.25	47.87 ± 8.98	45.92 ± 9.67	47.71 ± 8.41	0.21	0.845

† Exp: experimental group, ‡ Cont: control group.

3.2. Psychosocial CVD Risk Factor

In the control group, job stress was 1.09 ± 0.32 before applying the yoga program, and there was no change to 1.09 ± 0.30 after applying the program. In the experimental group, it was confirmed that it was 1.38 ± 1.80 before applying the yoga program and decreased to 1.02 ± 0.24 after applying the program. However, there was no statistically significant difference in the reduction of job stress between groups at each measurement point in the effect verification (p = 0.240). The depressive symptom score did not change significantly before and after the yoga program between groups, but in the effectiveness verification, there was a statistically significant difference in job stress reduction between groups at each measurement point (p = 0.008). In the case of health promotion behavior, it was confirmed that scores increased after applying the yoga program compared to before applying the yoga program in both the experimental group (109.13 ± 25.94 to 111.35 ± 15.56) and the control group (97.26 ± 22.85 to 98.82 ± 20.41). The difference score of the experimental group (−2.23 ± 3.08) was greater than that in the control group (−1.55 ± 1.22), and it was statistically significant between groups. However, in the effect verification between groups at each measurement point, there was no statistically significant difference in the decrease in health promotion behavior scores (p = 0.828) (Table 2).

Table 2. Comparison of Yoga Program's Effects between Experimental and Control Groups (N = 69).

Variables	Group	Pre-Test	Post-Test	Difference	*p*	Source	F	*p*
		Mean ± SD	Mean ± SD	Mean ± SD				
Depressive symptoms	† Exp.	19.44 ± 8.08	19.81 ± 3.61	−0.36 ± 7.97	0.798	Group	1.10	0.298
						Time	0.56	0.457
	‡ Cont.	21.36 ± 6.89	20.18 ± 6.88	1.18 ± 10.83	0.504	Group * Time	7.52	0.008
Job stress	Exp.	1.38 ± 1.80	1.02 ± 0.24	0.36 ± 1.81	0.280	Group	0.53	0.470
						Time	1.43	0.236
	Cont.	1.09 ± 0.32	1.09 ± 0.30	0.00 ± 0.37	0.980	Group * Time	1.40	0.240
Body weight (kg)	Exp.	61.10 ± 12.65	62.07 ± 12.66	−0.97 ± 5.88	0.364	Group	1.54	0.219
						Time	1.18	0.282
	Cont.	64.95 ± 11.15	65.08 ± 10.54	−0.13 ± 2.00	0.688	Group * Time	0.68	0.411
Waist circumference (cm)	Exp.	81.87 ± 8.01	79.21 ± 7.92	2.66 ± 2.47	<0.001	Group	0.51	0.478
						Time	29.21	<0.001
	Cont.	79.13 ± 8.27	79.16 ± 8.22	−0.03 ± 1.55	0.917	Group * Time	30.39	<0.001
Systolic blood pressure (mmHg)	Exp.	128.48 ± 10.38	127.07 ± 10.64	−1.41 ± 4.44	0.086	Group	0.01	0.961
						Time	1.24	0.270
	Cont.	127.47 ± 12.87	127.79 ± 13.14	−0.32 ± 3.77	0.609	Group * Time	3.07	0.084
Diastolic blood pressure (mmHg)	Exp.	81.04 ± 8.57	79.16 ± 8.11	−1.88 ± 3.09	0.002	Group	1.40	0.242
						Time	4.05	0.048
	Cont.	82.29 ± 8.97	82.66 ± 8.09	−0.37 ± 3.11	0.469	Group * Time	8.97	0.004
Total cholesterol (mg/dL)	Exp.	201.19 ± 32.16	201.45 ± 33.81	−0.27 ± 7.35	0.842	Group	2.12	0.150
						Time	0.71	0.402
	Cont.	192.76 ± 34.90	188.03 ± 30.46	−4.73 ± 28.70	0.316	Group * Time	0.89	0.348
Health promotion behavior	Exp.	109.13 ± 25.94	111.35 ± 15.56	−2.23 ± 3.08	0.475	Group	6.01	0.017
						Time	1.50	0.225
	Cont.	97.26 ± 22.85	98.82 ± 20.41	−1.55 ± 1.22	0.210	Group * Time	0.05	0.828
Health responsibility	Exp.	16.39 ± 6.99	16.10 ± 4.69	0.29 ± 5.79	0.782	Group	1.89	0.173
						Time	0.01	0.919
	Cont.	14.55 ± 5.57	14.74 ± 4.67	−0.18 ± 2.54	0.657	Group * Time	0.21	0.651

Table 2. *Cont.*

Variables	Group	Pre-Test	Post-Test	Difference	*p*	Source	F	*p*
		Mean ± SD	Mean ± SD	Mean ± SD				
Physical activity	Exp.	15.06 ± 6.18	17.13 ± 5.92	−2.07 ± 6.99	0.111	Group	3.54	0.064
						Time	3.46	0.067
	Cont.	13.95 ± 4.71	14.16 ± 3.84	−0.21 ± 5.27	0.617	Group * Time	2.29	0.134
Nutrition	Exp.	19.77 ± 4.42	19.16 ± 4.28	0.61 ± 3.78	0.371	Group	12.38	0.001
						Time	1.02	0.317
	Cont.	16.42 ± 3.43	16.34 ± 3.54	0.08 ± 1.76	0.784	Group * Time	0.606	0.439
Spiritual growth	Exp.	20.55 ± 5.22	21.16 ± 5.77	−0.61 ± 4.75	0.478	Group	4.19	0.045
						Time	0.05	0.823
	Cont.	18.58 ± 4.35	18.18 ± 5.41	0.39 ± 3.30	0.466	Group * Time	1.08	0.304
Interpersonal relation	Exp.	20.32 ± 5.22	20.74 ± 4.47	−0.42 ± 2.77	0.405	Group	4.13	0.046
						Time	0.65	0.422
	Cont.	18.42 ± 3.78	18.53 ± 4.17	−0.11 ± 2.62	0.806	Group * Time	0.23	0.630
Stress management	Exp.	17.03 ± 5.04	17.06 ± 2.42	−0.03 ± 4.57	0.969	Group	1.17	0.284
						Time	1.14	0.290
	Cont.	15.34 ± 4.18	16.87 ± 6.11	−1.53 ± 7.01	0.188	Group * Time	1.05	0.310

† Exp: experimental group, ‡ Cont: control group, * interaction.

3.3. Physical CVD Risk Factor

After the yoga intervention, the experimental group showed a significant reduction of waist circumference from 81.87 ± 8.01 cm to 79.21 ± 7.92 cm ($p < 0.001$), but the score of the control group was not changed. Also, there was statistically significant difference in the decrease of waist circumference scores in the effect verification between groups at each measurement point ($p < 0.001$). Furthermore, diastolic blood pressure decreased after applying the yoga program in the experimental group (81.04 to 79.16), but there was no change in the control group. Also, there was a statistically significant difference in the decrease of diastolic blood pressure at each measurement point between groups ($p = 0.004$). On the contrary, there were no significant changes in waist circumference or diastolic blood pressure in the control group. In addition, in the case of body weight or systolic blood pressure, there was no significant change in the experimental group and the control group when comparing before and after applying the yoga program. As a result, the yoga program was found to be effective in reducing waist circumference and diastolic blood pressure ($p = 0.004$) (Table 2).

4. Discussion

This study applied a 12-week (24 sessions) yoga program (warm-up, yoga poses, cool-down) to workers in small enterprises—a pool of workers who are particularly vulnerable in terms of organized health management due to a lack of on-site health managers in small enterprises—in an attempt to lower CVD risk factors including psychosocial factors such as job stress, depression, and health promotion behaviors.

The experimental group who underwent the yoga intervention showed a decrease in job stress score after the intervention, even though it was not statistically significant. This is a similar result to that of a previous study showing a reduction in job stress in the experimental group after providing a yoga program to office workers [28]. In the previous study, the yoga program was designed as a 10-week, 20-session program with two 60-min sessions per week [28]. That program was similar in content to our program, which comprised warm-up, yoga posture, breathing, and meditation, and both programs led to reductions in job stress, though the duration of the sessions differed. A previous study found that yoga programs based on meditation and breathing have positive effects on social and emotional changes, namely providing psychological stability and reducing job stress, by activating the parasympathetic nerves and relaxing tense muscles [26]. Even though the score of job stress was not significantly decreased in this study, we could speculate that our yoga program could possibly lead to positive outcomes in terms of job stress in a future study. Also, we thought that a yoga program tailored to the working patterns of the workers, set to begin before work in the morning, could help relax the workers' minds and invigorate them, increasing their happiness and subsequently reducing job stress.

Depression in workers has been identified as a predictor of "presenteeism", which refers to work and productivity loss, increase of health management expenses, and indirect productivity loss induced by working with a health problem [40,41]. The experimental group that underwent the yoga intervention did not show significant changes in depressive symptom scores after the intervention. In other words, the yoga intervention was found to have no impact on the depression score in this study, which is largely similar to the findings of a previous report stating that a 16-week yoga program did not significantly decrease depression levels—though depression levels dropped at certain time points—in medical students [42]. These findings call for additional studies with longer follow-ups, because it is difficult to establish the effects of interventions on social and emotional factors, such as depression, in the short term [43]. Longer yoga programs are expected to induce significant changes. In contrast to our findings, there was a study reporting that a 12-week yoga program significantly decreased depression scores in women with post-traumatic stress disorders [44]. Such differences in results may be attributable to the limitations of our sample; we speculate that the yoga intervention might have led to significant changes of depression scores if we had screened out the subjects with high depression scores and applied the yoga intervention to this subset of subjects. In the Western countries, the criteria for probable and definite depression are generally 16 and 25 points, respectively. In a depression epidemiological survey on South Koreans by Cho and Kim in 1993 [34], investigators suggested using 21 points as the baseline cut-off for screening for suspected depression and 25 points for screening for definite depression. CES-D scores at baseline in the experimental and control groups were 19.44 and 21.36, respectively. Compared with the level of CES-D (23.2 ± 11.62) of a previous study conducted to find out affecting factors on depression among female workers in small-sized workplaces [45], the level of depressive symptoms of participants in the experimental group in this study was relatively low. Also, these depressive symptoms' level in the study population belonged to the normal range. Thus, replication studies using a sample of participants with high depression scores are needed to investigate whether yoga interventions have a positive effect on workers' depression.

Usually, small enterprises lack an on-site health manager to provide systematic health management for workers, rendering it difficult to apply long-term health promotion programs and consequently hindering efforts to improve workers' health. We speculate that these factors would have contributed to the lack of significant health-promoting behaviors among the workers who underwent our yoga program. Studies on health promotion programs based on participatory action-research are underway in the field of industrial health research to ensure easy and long-term access [2]. This is a bottom-up type of intervention, in which participants proactively discover their health problems, and find and apply solutions with the help of researchers, as opposed to a top-down intervention in which the researcher identifies the problem, plans and designs a program to solve it, and applies the program to the participants. This type of intervention would be appropriate for small enterprises that lack on-site occupational health managers [2,46]. In fact, at least one study verified the effects of a participatory action-oriented training (PAOT)-type of intervention in lowering cholesterol, fasting glucose, body weight, and blood pressure while improving health-promoting behaviors in workers with a CVD risk [47]. The authors pointed out that many health promotion projects conducted in the worksites do not have any practical health benefits for workers because they are relatively short-term and passive, and also argued that methods of applying these health promotion interventions should be changed to address such limitations [2,46]. In addition, numerous studies emphasize the importance of community competency-strengthening projects as a strategy to ensure that enterprises continue to implement health promotion programs on their own even after the conclusion of the study.

A previous study reported that taking a community competency-strengthening approach developed leadership and formed partnerships, which improved the self-regulation of health management, ultimately improving each individual participant's health-related quality of life and health promotion behaviors [2,47]. Based on these outcomes, we expect that efforts by small enterprises to foster health leaders for workers as a strategy to strengthen community's competence would also serve as an effective strategy for them to continue implementing health promotion programs on their own, and doing so would ultimately facilitate workers' health-promoting behaviors and improve their health-related quality of life. In light of these findings and suggestions, we are planning to develop and assess the effects of a PAOT-based health promotion program and competence-strengthening projects, such as training health leaders, as a strategy to lower CVD risks in workers of small enterprises. Through these studies, we will develop health promotion program strategies tailored to small workplaces that have low access to health promotion programs and generate long-term effects, contributing to developing policies to reduce CVD in workers of small enterprises. Furthermore, a previous study asserts that assessing the perceptions of the participants is important to improve the quality of clinical research [48]. Unfortunately, we did not collect data on participants' perceptions of this yoga program. Therefore, we propose to investigate the research participants' perception on the program in the follow-up study and use it in the intervention study to improve the quality of the research.

According to a meta-analysis of 61 studies investigating the relationship between blood pressure and mortality [44], a reduction of 2 mmHg of systolic blood pressure reduces mortality caused by ischemic heart disease by 7% and mortality caused by stroke by 10%. We verified that the yoga program developed in this study reduced diastolic blood pressure in workers of small enterprises, who are at higher risk of CVD than are those of medium-sized or larger enterprises, thereby confirming that this program is effective in lowering blood pressure, a critical physiological index related to CVD risks. Furthermore, physical measurement indexes such as waist circumference were significantly decreased in this study. Previous studies asserted that abdominal obesity has been identified as an important risk factor for metabolic syndrome and CVD [49,50]. Also, the other studies have shown that waist circumference was reduced relatively more in women than men [49,51]. Furthermore, Siu and colleges presented that one year of regular yoga training was effective on the improvement of waist circumference in middle-aged and older adults with metabolic syndromes [52]. Although it was analyzed that there was no gender difference between the experimental and the control group in the homogeneity test of this study, the ratio of women in the experimental group was relatively higher than that of the control group. Also, the average age of the participants in this study was 48.15 in the experimental group and 49.46 in the control group, which is considered to be a middle-aged group. Therefore, it was considered that the yoga program was effective in reducing waist circumferences in this study. In order to more reliably confirm the effect of yoga on the reduction of waist circumference, additional studies on workers considering age and gender are needed.

Our study has several limitations. First, sample size was relatively small (experimental group, n = 31; control = 38). Second, this study did not consider the level of individual capacity for the yoga program. Third, the study period was short to expect psychological effects such as depression and job stress. Therefore, a longer period of interventional study is needed in the future.

5. Conclusions

This study investigated whether a 12-week yoga program is effective in lowering psychological and physical measurements related to CVD risks in workers of small enterprises by using a nonequivalent control group design. The findings showed that the yoga program was effective in reducing physical measurements such as waist circumference and diastolic blood pressure in workers of small enterprises. However, this program could be an effective and efficient health program for the blue-collar workers who work in small-sized workplaces. Therefore, these findings provide evidence that a yoga program may serve as a new exercise strategy for feasibility among Korean workers who work in small-sized workplaces.

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