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DEVELOPMENT OF A FRAMEWORK FOR DETERMINING THE OPTIMAL WINDOW SIZE FOR MAXIMIZING OCCUPANT PSYCHOLOGICAL SATISFACTION AND BUILDING ENERGY PERFORMANCE

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ABSTRACT

Windows are a key design element that can affect the building energy performance and occupant psychological satisfaction. While smaller windows can increase building energy performance, they can also lower occupant psychological satisfaction. Despite the importance of determining the optimal window size by considering the building energy performance and occupant psychological satisfaction and their trade-off relationship, few studies have proposed a window size that considers both aspects. To solve this problem, this study proposed the following framework capable of accounting for both aspects in determining the optimal window size: (i) experimental settings for measuring the occupant psychological satisfaction based on the window size; (ii) virtual environment creation using *SketchUp*, *3dsMax*, and the *Unreal engine*; (iii) measurement of occupant psychological satisfaction using questionnaire survey; (iv) measurement of building energy performance using *SketchUp* and *EnergyPlus*; and (v) selection of the optimal window size using the Pareto optimal solution. Using the proposed framework, even non-specialists of virtual reality or energy simulations can easily measure building energy performance and occupant psychological satisfaction by *SketchUp* modeling. Based on the building energy performance and occupant psychological satisfaction measured as such, the optimal window size can be determined according to building usage and conditions as well as client requirements.

Keywords: Virtual Reality (VR); Occupant psychological satisfaction; Building energy performance; Building energy consumption; Pareto optimal solution

NONMENCLATURE

VR	Virtual reality
VE	Virtual environment
WWR	Window-to-wall ratio
CLT	Central Limit Theorem

1. INTRODUCTION

Global warming due to rapid industrialization and population increases has led the whole world to make efforts in reducing energy usage and carbon dioxide emissions. Particularly, about 40% of the total energy usage is from buildings. Thus, building designs that can drastically reduce energy consumption have become of huge interest [1]. Windows are a key design element that occupy over 10% of the energy consumption of a building [2] and determine occupants' comfort, including thermal and visual comfort [3]. Due to such importance of window design, various studies have been conducted on the energy consumption of windows based on heating, cooling and lighting demand. Furthermore, other studies have focused on determining the optimal window size by considering all those items as parameters [4]. Meanwhile, windows are a design element that affects not only the aforementioned building energy performance, but also occupant psychological satisfaction [6]. Therefore, it is crucial to determine an optimal window size by considering them at the same time. Studies that analyzed building energy performance

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by window size showed that the smaller the area of a window, the less the energy consumption [3,4,7,8]. On the other hand, studies that analyzed occupant psychological satisfaction by window size showed that the larger the area of a window, the more the psychological satisfaction increased [6,9–11]. As such, it is difficult to determine the optimal window size by considering both aspects that are in a trade-off relationship with each other. Accordingly, few studies have considered both aspects in determining the optimal window size. To overcome this difficulty, this study aims to propose a framework based on which the optimal window size can be determined by allowing non-specialists to easily measure building energy performance and occupant psychological satisfaction and consider both of them at the same time. The following effects can be expected by using the proposed framework: (i) by presenting a method to create virtual environments based on *SketchUp* and the *Unreal engine*, this framework allows more accessible and more realistic virtual environments than the existing methods, while saving time, money and labor. (ii) *SketchUp* modeling file can be used in *EnergyPlus* by converting its geometry with *OpenStudio*, which makes the analysis of building energy performance easier. Finally, (iii) by finding the Pareto optimal solution with the quantification of the performance of these two factors, the optimal window size that considers the building energy performance and occupant psychological satisfaction can be determined.

2. MATERIAL AND METHODS

2.1 Step 1: Experimental setting

Three stages are required for the establishment of an experimental setting. First, the window size can be set by adjusting the window-to-wall ratio (WWR) to a certain ratio (e.g., 5%, 10%, and 15%). Here, the designer sets the variation of the window size based on the required WWR. Second, there should be more than 30 experiment participants according to the Central Limit Theorem (CLT). According to CLT, a larger sample group follows the normal distribution, and thus, more participants will result in statistically more reliable results. Third, since it is difficult to recruit different participants according to many different window size variations, the within-group effect can be analyzed using the crossover study method. Each experiment participant experiences all variations of window size, at which the experiment order is randomly distributed to prevent the learning effect (e.g., when one expects the order of the increase or decrease in the WWR)

2.2 Step2: Creating virtual environment

Creating a virtual environment includes three stages. First, based on the information of a building to be designed with *SketchUp*, the buildings, trees, mountains, and roads outside as well as the interior of the room are modelled in 3D. At this point, the *3D warehouse* of *SketchUp* and 3D objects required by *Autodesk 3dsMax Asset Library* are imported and used. Second, the 3D modeling file from *SketchUp* is imported and covered with materials in *3dsMax*. Third, the 3D modeling file, revised and completed in *3dsMax*, is imported to the *Unreal engine*, and the directional light is set to the altitude and azimuth of the sun, and the point light is set according to indoor lighting. Next, the roughness, specular and metallic features of the covered materials are adjusted according to the *Blue print* (i.e., *Unreal engine*'s own the programming language) to complete real-time rendering. Finally, the resulting file is built and exported to the package file of the virtual reality (VR) mode. The process is completed by connecting a VR device. Fig. 1 shows the flow charge of the whole process, and Fig. 2 shows an example of an experimental

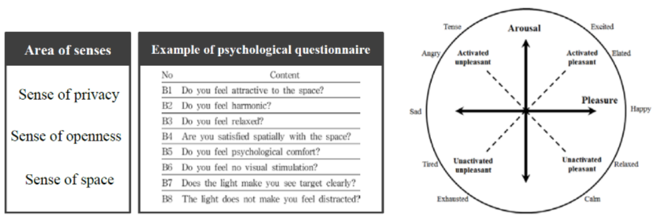
Fig 1 The process of creating virtual environment.

Fig 2 Examples of virtual experimental environment in *Unreal engine*.

environment to measure the occupant psychological satisfaction based on the WWR in the *Unreal engine*.

2.3 Step 3: Measuring occupant psychological satisfaction

There are two kinds of questionnaire surveys that can be used to measure occupant psychological satisfaction. The first method is to measure satisfaction by assembling the direct responses of participants on the sense of privacy, openness, and space that change according to the WWR. The other method is to use a questionnaire survey that determines participants' state of mind defined by the circumplex model of affect [12,13]. The items used in this questionnaire survey are: calm, peaceful, restful, in control, hectic, rushed, stimulated, exhilarated, excited, dull, bored, overwhelmed, significant, important. As such, relaxation and excitement are measured and summarized to determine occupant psychological satisfaction. The above two survey methods can be measured in a 7-point Likert scale. Fig. 3 shows the concept of survey form of the two methods.



(a) Psychological questionnaire by area (b) Circumplex model of affect

Fig 3 Two methods of satisfaction questionnaire.

2.4 Step 4: Measuring building energy performance

To measure building energy performance based on the heating, cooling and lighting demands that change according to the WWR, the study uses *EnergyPlus*, an energy simulation tool. First, the SketchUp modeling file used for creating the virtual environment is imported to the building modeling in *EnergyPlus* through *OpenStudio*. *OpenStudio* has *SketchUp* Plug-in, and the user can create the geometry required in *EnergyPlus*. Second, the detailed information parameters on interior lighting and air-conditioning devices based on the information of the target building are entered using an *IDE Editor*, and the properties of the outer walls and heat transmission coefficient are entered. Third, the weather conditions of the target building location (i.e., outdoor air temperature, wind speed, wind direction, wind pressure, radiation, cloud cover, and precipitation) are entered. The weather data are collected from the National Weather Service's website. Then, the energy consumption in identical parameters except the WWR is calculated according to the WWR. Fig. 4 shows the energy simulation process by *Energy Plus* and *SketchUp*.

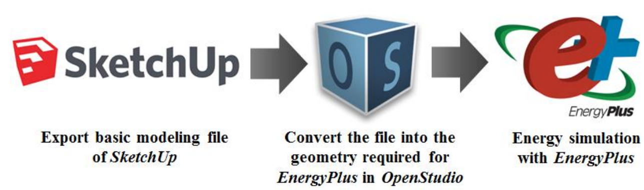


Fig 4 The process of running energy simulation with *EnergyPlus* using modeling file of *SketchUp*.

2.5 Step 5: Multi-objective optimization using Pareto optimal solutions

To consider both the occupant psychological satisfaction and building energy consumption based on the WWR, a multi-objective optimization should be performed using the Pareto optimal solution in order to determine the optimal WWR. The Pareto optimal fitness function that maximizes an objective function A (i.e., occupant psychological satisfaction) while minimizing an objective function B (i.e., building energy performance) is shown in Eq. (1). The WWR with the lowest result from Eq. (1) can be determined as the optimal WWR. The weighting value is determined by the importance of occupant psychological satisfaction and building energy consumption based on the building usage, location and client requirements.

$$\mathit{Fitness\ Function}\ (i) = \sqrt{\omega_A \times (1 - S_A)^2 + \omega_B \times (S_B - 0)^2} \quad (1)$$

$S_A = \mathit{Psychological\ satisfaction}$
$S_B = \mathit{Psychological\ satisfaction}$
$\omega_A = \mathit{Weight\ of\ psychological\ satisfaction}$
$\omega_B = \mathit{Weight\ of\ energy\ consumption}$
$\omega_A + \omega_B = 1$

3. CONCLUSIONS

This study proposed a framework with which to determine the optimal window size by considering the occupant psychological satisfaction that changes according to the window size and the building energy performance caused by heating, cooling and lighting demand. *SketchUp* was used to perform 3D modeling for VR to analyze occupant psychological satisfaction, and thus, an easier and faster analysis of building energy consumption can be performed using *EnergyPlus*. Therefore, this study proposed a framework that considers both aspects more easily.

This study (i) proposed a framework that could be used by non-specialists with *SketchUp* and *EnergyPlus*; (ii) can produce more reliable and realistic results on the occupant psychological satisfaction experiment using the *Unreal engine* by allowing for the experiment environment with identical design parameters, except for the WWR; and (iii) can adjust the significance of occupant psychological satisfaction and building energy performance in the Pareto optimization process according to the type and conditions of the building along with client requirements. Therefore, the designer can save time, costs, and labor while determining the optimal window size that can meet the occupant psychological satisfaction and building energy performance at the same time. From the perspectives of the client rather than the designer, the cost is more likely to be focused on than energy consumption. Therefore, future research can consider Life Cycle Costs (LCC), which changes according to the window size, as an objective function. Besides the LCC, a Life Cycle Assessment (LCA) can be implemented as another objective function to examine the effects of window size variation on the environment. Future research can propose an optimal design alternative in the context where not only the window size but also other design elements such as the material of the walls and the floors, lighting, and furniture by considering technical, economic, environment, and psychological aspects.

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