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Integrated BIM-Parametric Workflow-Based Analysis of Daylight Improvement for Sustainable Renovation of an Exemplary Apartment in Seoul, Korea

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Abstract: More than 60% of housing in South Korea consists of mass constructed apartment neighborhoods. Due to poor quality construction materials and components, the average operative life of apartment buildings is 20 years. The rapid degradation and low maintenance condition of transparent and semi-opaque components, as well as the limited daylight access in the standard apartment layout, are cause for the lower visual comfort of occupants. This research analyzes the improvement in visual comfort for the renovation of an exemplary apartment unit in Seoul, using Building Information Modeling (BIM) and parametric environmental analysis tools. The existing apartment is virtually reconstructed with BIM software. The building model is exported to Computer-Aided Design software to execute parametric daylight analyses through environmental simulation software. An enhanced modular building envelope and apartment layout are developed to reduce the energy demand for heating, cooling, artificial lighting, and to improve visual and thermal comfort. The visual comfort analysis of the refurbished apartment results in average improvements of 15% in terms of Daylight Factor and 30% of daylight autonomy. Therefore, this research proposes, the renovation of aged Korean apartment buildings to enhance daylighting and visual comfort.

Keywords: daylight analysis; visual comfort; BIM-parametric refurbishment workflow

1. Introduction

Mass construction of apartment neighborhoods in South Korea started with the enforcement of a series of national housing plans developed during the 1970s and 1980s [1]. The aim of these consecutive national housing plans and policies was to resolve the housing shortage that the country suffered from the end of the Korean War [2]. Between 1970 and 2010, 8 million apartment buildings were constructed in South Korea [3]. During the years of economic development (1960–1992) [4], the Korean government employed multiple strategies to reach the goals set by national housing plans: industrialization of the building sector and mass construction of standard apartments as well as support for the private initiative for the realization of residential buildings [5]. A standard apartment unit layout was developed on the basis of the traditional Korean house, the Hanok [6], to facilitate industrialized mass construction and the replicability of multistory apartment buildings [7]. However, to rapidly increase the housing stock, poor quality materials and construction components were utilized [8,9]. Additionally, real estate sector speculation caused a further reduction of the quality and quantity of construction materials, by concurrently increasing apartment unit selling prices to maximize profits [10]. Accordingly, the quality of the apartment stock in South Korea is comparably low, with an average building life time of

20 years [11]. Approximately 46% of apartment buildings (3.7 million buildings (Figure 1)) require extensive renovation, due to poor structural conditions, degradation of construction components, and obsolescence of building technical systems [12,13]. Aged apartment buildings require higher heating and cooling energy costs, due to comparably high air infiltration through the building envelope [14], and degradation of construction components, such as insulation [15,16] and windows [17]. The visual comfort of occupants in the standard apartment unit is low, due to limited daylight access, caused by the configuration of the apartment unit layout [18]. Additionally, the daylight transmission of windows decreases during their lifetime, due to the accumulation of soiling, scratches, and decay of the optical properties of the panes [19,20].

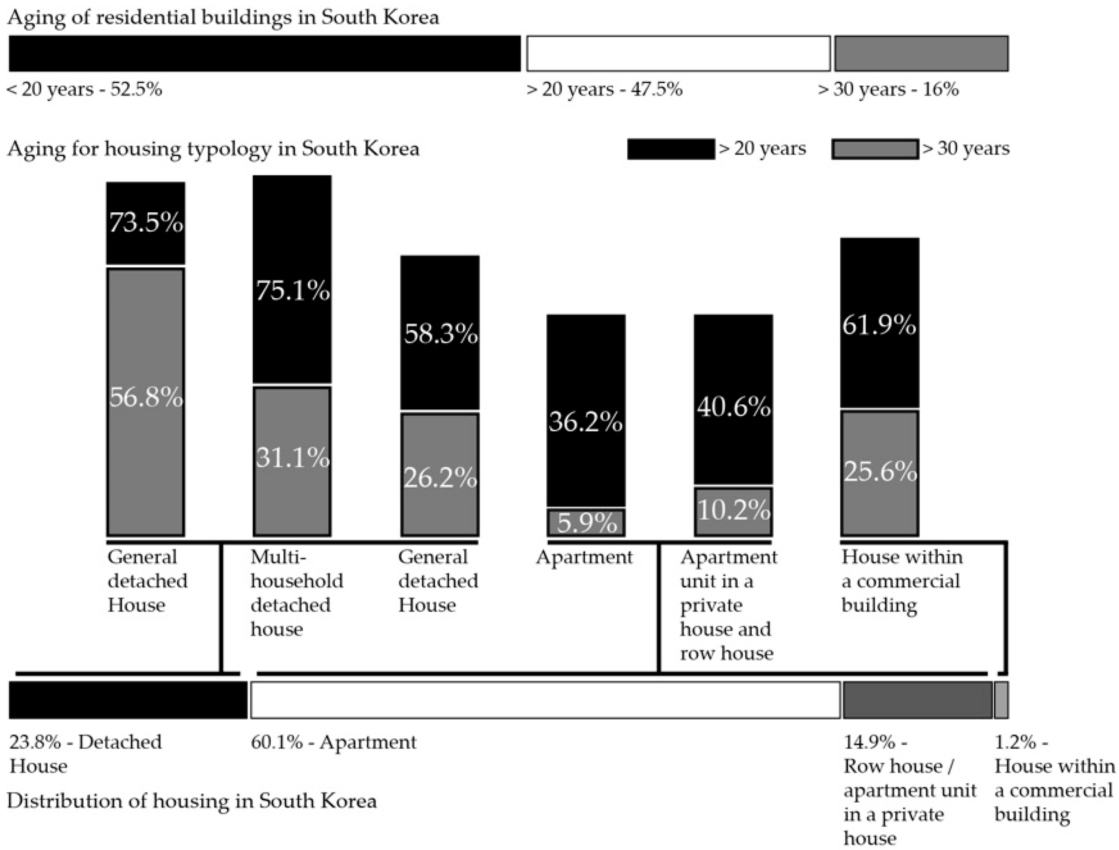

Figure 1. Distribution of housing typologies and relative aging for residential buildings in South Korea (according to data from Korean Statistical Service (Kosis) [13]).

After 20 years of building operation, occupants of apartments in Korea are often unable or unwilling to pay the required high building maintenance and renovation costs [21]. Redevelopment strategies for apartment neighborhoods were established in the 1980s under the Joint Redevelopment Project (JRP) plan [22]. JRP consist of the demolition of aged apartment neighborhoods, and the construction of new buildings with higher number of floors and Floor Space Index (FSI) [23]. Previous occupants receive monetary compensation from real estate speculators, and relocate in peripheral low-income districts [24]. JRP-based redevelopments of apartment neighborhoods are responsible for the production of demolition waste [25], emissions from new construction [26], and gentrification [27].

From the beginning of the 21st Century, the Korean Government has begun to enact a number of laws that are aimed at the renovation and requalification of dilapidated apartment neighborhoods [28]. In 2014, the "vertically extended remodeling" [12] plan was established to motivate construction companies and building owners to invest in building renovation projects. Accordingly, constructors are allowed to increase the amount of floors for aged apartment buildings by two or three levels, if the expansion works are combined with the energetic optimization of the existing construction. The amendment of the Housing Act [29] additionally provided the opportunity for dwellers to increase the usable area of their own apartment by up to 40% of the previous floor space in the framework of renovation projects that increase the energy efficiency of existing buildings. In 2008, South Korea adopted a comprehensive sustainability plan for all economic sectors under the "Low Carbon Green Growth" initiative [30]. Through the "Green Growth" plan, South Korea has committed 2% of its Gross Domestic Product (GDP) towards the introduction of alternative energy technologies and 30% reduction of Greenhouse Gasses (GHG) emissions from 2009 to 2020 [31]. The Housing Act has therefore been amended to include the progressive reduction of building envelope U-values in new constructions. New residential buildings should accordingly reach zero energy consumption, and nonresidential buildings should cut energy requirements by 60%, by 2025 [32]. Furthermore, the "Green Growth" plan foresees the construction of 1 million green homes by 2020 [31].

Sustainable initiatives for the renovation of apartment buildings aim for the improvement of the energy consumption of residential constructions, by increasing the thermal insulation levels of the building envelopes [33–35]. Studies on the renovation of apartment buildings concentrate on developing optimal strategies for the expansion of the usable floor space of apartment units, in combination with the improvement of energy efficiency [36,37]. However, less attention is paid to analyzing the impact of renovation projects on the well-being of occupants, including thermal and visual comfort. The South Korean sustainable certification system, G-Seed [38], does not include indications concerning minimum and maximum thresholds of acceptable daylight levels for visual comfort in residential buildings [39]. Research on daylight performance optimization focuses on the energy efficiency of improved window systems and the calculation of heating and cooling energy demand reduction by changing the window-to-wall ratio (WWR) [40,41]. Studies on visual comfort concentrate on providing design strategies to attenuate glare and increase daylight [42] and comparing the effect of different apartment building layouts and shapes on the visual comfort of occupants [43]. However, an integrated approach for the reduction of energy demand for heating and cooling with the increase of visual and thermal comfort is still missing. A specific approach based on measuring daylight levels in apartment buildings, and accordingly the development of visual comfort improvement strategies, is therefore required. In particular, current studies on the simulation of daylight levels in residential buildings [44,45] concentrate on providing data on levels of natural light in apartment buildings located in Korea, without providing indications for the improvement of visual comfort through the renovation of the apartment buildings. In contrast, the development of models for integrated sustainable building planning concentrates on the optimization of building designs based on interrelated variables [46]. The aim of such models is the definition of optimal building shapes and envelopes to maximize day lighting and natural ventilation. However, the development does not take advantage of modern technology available both for building design and environmental analysis.

Studies of building energy demand and indoor comfort have been enhanced by the introduction of freeware software for environmental analysis [47]. Building Information Software (BIM) in architectural practices facilitates the control of building quantities, design precision, the exchange of building data and construction component information between different file formats, specialist, and analysis tools [48]. However, recent studies show a trend in modeling complex systems such as daylight optimization in building designs. Parametric tools are employed to assess the impact of shading on windows according to specific variables, such as geometry, dimensions, and transparency of the shading systems [49]. Accurate daylight modeling in residential and nonresidential buildings facilitates the development of effective design solutions for optimized daylighting [50]. The use of BIM allows also the assessment of different building design options for the reduction of buildings' service energy consumption [51].

This research developed an integrated Building Information Modeling-parametric framework for the renovation of aged apartment buildings in South Korea, focusing on daylight improvement. An existing apartment building in Seoul has been selected as an exemplary case study, to demonstrate the use of the BIM-parametric framework. The building has been virtually reconstructed through BIM software. A daylight simulation of a reference apartment unit in the building has been executed using parametric environmental analysis software. The daylight simulation has been executed parallel to energy simulations and thermal comfort analysis of the apartment unit in order to provide an integrated energy and comfort model for the exemplary apartment buildings. The energy and daylight simulations took into account the specific thermal and optical properties of the construction components, as well as the distribution of spaces in the standard layout of the reference apartment unit. Results from the daylight simulation of the existing building were used to develop an enhanced building envelope system made of modular panels. The enhanced building envelope system includes improved WWR and window components to provide better daylight transmission and distribution in the renovated apartment. Additionally, based on the results of the daylight simulation, a new apartment unit layout has been developed to improve the visual comfort of occupants and the available usable floor space. The results from the daylight and energy simulations of the renovated apartment showed improvements in visual and thermal comfort, as well as the heating and cooling energy demand.

This research aims to develop a streamlined integrated BIM-parametric workflow for the renovation of apartment buildings in South Korea, and Asia in general. Through the use of the integrated BIM-parametric framework, construction data can be stored in a BIM model and multiple renovation solutions can be analyzed using parametric environmental analysis tools. Furthermore, the BIM-parametric renovation framework allows energy, daylight, and comfort analyses to be integrated through a range of building simulations. Accordingly, the integrated framework allows the discovery of interdependencies between energy, daylight, and comfort, and the optical and thermal properties of building components in order to develop sustainable renovation solutions. The proposed integrated framework can increase the feasibility of renovation projects by reducing the required time and related monetary costs for the analysis and improvement of existing aged buildings.

2. Materials and Methods

The virtual BIM reconstruction of the exemplary apartment building located in Seoul has been executed with the software Autodesk Revit [52]. Construction data, retrieved from the survey of the existing apartment building and literature on the construction of housing in South Korea, have been stored in the virtual BIM building model using construction component families. Revit families are virtual modular components that store information, such as the type and number of material layers as well as the thermal properties of the building construction elements. Families are independent from a single building project, and can be exported and reutilized in other BIM-projects. Virtual model geometries of the apartment building analyzed that have been generated within the BIM-software have been exported to the Computer-Aided Design (CAD) software, Rhinoceros SR5 [53] through the Autodesk proprietary DWG ACIS solid format. Geometries generated in Rhinoceros can be imported backwards into Revit with the same ACIS format.

For the energy and daylight simulations of the reference apartment unit in the building, the component groups Ladybug and Honeybee from the Ladybug tools [54] plug-in for the parametric suite Rhinoceros Grasshopper 0.9 [55] have been utilized. Ladybug tools use geometries generated in Rhinoceros as virtual models for energy and comfort simulations executed with free environmental analysis software. Environmental software connected through the Ladybug tools with Rhinoceros include Radiance 5.2 [56] for daylight simulations, THERM 7.5 [57] for the calculation of the thermal gradient through construction components of the building envelope, WINDOW 7.6 [58] (Lawrence Berkeley National Laboratory) for the simulation of optical and thermal properties of windows systems, and Energyplus 9.0.1 (US Department of Energy) [59] for the simulation of heating and cooling energy demand.

The BIM-parametric renovation framework consists of exporting BIM geometries and construction data produced with Revit to Rhinoceros. Building energy, daylight, and comfort simulations are executed through the use of the parametric Ladybug tools. The parametric tools allow changing specific variables related to construction components, such as the U-value and thickness of insulation, as well as the g-values of windows. Accordingly, building energy simulation can be executed by transferring data between the parametric tool and Energyplus. The daylight analysis of the building model is produced in Radiance after importing the geometries of construction components and their optical properties. The natural light distribution simulation in interior spaces is executed in Rhinoceros. The visualizing tool allows visualizing different daylight and visual comfort indexes through two- and three-dimensional distribution maps. Through the different building simulations, improvement strategies for the renovation of existing aged buildings are developed. The optimization of the improvement strategies follows an iterative procedure. The building simulation aims for quantification of indoor comfort improvement and service energy minimization of different building envelope renovation measures. Renovation strategies include, among others, the replacement of existing windows with better performing components and changes of the Window-to-Wall Ratio (WWR). The building simulations can be executed again on the renovated virtual building model and improvements quantified. Accordingly, the improvement strategies for the renovation of aged buildings can be refined and enhanced, to increase the performance of the building refurbishment project. The framework is backward compatible, as geometries and the construction data parametrically generated in Rhinoceros and based on environmental simulations can be exported again to the BIM-software.

For application of the BIM-parametric framework in the case of the exemplary apartment located in Seoul, construction data and the thermal and optical properties of the building components and materials used for the environmental simulations have been exported from the reconstructed virtual BIM-model to the data spreadsheet and elaboration software Microsoft Excel 2017 [60] using the in-built functionalities of the BIM program. The construction data stored in Microsoft Excel have been imported into Ladybug, using the Grasshopper plug-in, Bumblebee [61]. Accordingly, construction data exported from Excel to Rhino Grasshopper have been associated through the use of Ladybug tools with their relative building components and model geometries exported into Rhinoceros from Revit. The combined geometrical information and associated construction data defined the parametric building model for energy, daylight, and comfort simulations using environmental analysis software. The parametric building model has therefore been imported into the environmental analysis software for the execution of energy and comfort simulations. Accordingly, results from the energy and comfort simulations have been imported from the environmental analysis software into Rhinoceros through Ladybug. Simulation results for the reference apartment have been visualized through maps of the distribution of heating and cooling energy loads, color-coded grids measuring daylight, and false-color 3D-rendering displaying the intensity of daylight in the different rooms of the apartment unit.

The processes involved in the environmental analysis of the building construction, the development of the enhanced building envelope system, and the quantification of improvements in terms of energy demand and visual and thermal comfort define the integrated BIM-parametric renovation workflow. The BIM-parametric renovation workflow (Figure 2) has been developed and published in previous research by the authors [62].

This study focuses primarily on the improvement of daylight and visual comfort of the exemplary apartment unit. The information regarding daylight analysis and visual comfort improvement is summarized in the BIM-parametric renovation framework:

1. Virtual building reconstruction using BIM: the exemplar building construction is virtually reconstructed in Revit. Accordingly, construction elements, such as windows and glazing systems, are collected in specific construction families.
2. Climate and solar radiation analysis of the building: apartment building geometries are exported from the virtual Revit model to Rhinoceros for simulation of the annual global solar incident radiation on the building envelope using Ladybug. For the purpose, the building envelope model is subdivided into single partitions measuring a maximum 100 cm × 100 cm. The solar radiation analysis allows the selection of a reference apartment unit in the building for the energy, daylight, and comfort simulations. The reference apartment unit is selected according to the average solar radiation received during a whole year, calculated for all units within the building.

3. Building envelope analysis: Through direct survey and a WINDOW simulation of window components installed in the exemplary apartment building, the transmission index of glass panes (g-value) and U-value of the entire glazing system are calculated. Additionally, optical properties of construction components, such as Red/Green/Blue (RGB) reflections, roughness, and specularity, are defined using data on common materials that are available online [63].
4. Visual comfort analysis: A horizontal grid-based (spacing between sensors: 10 cm, grid height: 80 cm) analysis of daylight for the indoor spaces of the reference apartment is executed using Radiance. The following daylight metrics are measured.

    a. Daylight Factor (DF): Percentage of exterior natural light produced by a diffuse overcast sky received in indoor spaces.
    b. Daylight Autonomy (DA): Percentage of the time in a year, when the minimum illuminance threshold of 300 lux is exceeded in indoor spaces.
    c. Useful Daylight Illuminance (UDI): Percentage of the time in a year when illuminance values measured in indoor spaces range between the minimum threshold of 300 lux and the maximum threshold of 700 lux. The maximum threshold has been defined taking into account the function of the different spaces in residential buildings and the requirements for sensible user groups (the elderly, children, and so forth).

5. Development of improvement strategies: Partially based on the results of the daylight simulation and the visual comfort analysis, an enhanced building envelope is developed. Additionally, the results and observations of Energyplus simulations and thermal comfort analysis of the existing apartment also affect the design of the enhanced building envelope system. The enhanced building envelope system consists in modular panels that can be attached to the existing apartment construction. The modular envelope panel construction includes improved insulation, as well as window components and WWR, a shading system, and Building Integrated Photovoltaics (PV) panels. The enhanced building envelope provides lower building envelope U-values and increased window g-values; a shading system composed by variably oriented blinds and the production of renewable electricity through the BIPV panels. Accordingly, the improved transmission index (g-value) and thermal properties of new windows modules included in the enhanced building envelope panels are calculated with the software WINDOW. Optical properties of the new window components, such as RBG reflectance, roughness, and specularity of the frame, are further determined according to the relative material properties in the online databases. Additionally, an improved apartment layout is developed to provide better daylight access for indoor spaces, and extend the usable floor space of the renovated apartment.
6. Quantification of improvements: The daylight simulation and the visual comfort analysis metrics defined in phase 4 are executed using construction data from the enhanced building envelope. Results from the simulation of the renovated apartment unit are compared with the data from the simulation of the existing condition to quantify improvements in terms of daylight and visual and thermal comfort.
7. Virtual building renovation construction using BIM: Modular panel families are parametrically defined in Rhinoceros according to the new geometrical, thermal, and optical properties calculated for the enhanced building envelope system. Accordingly, panel geometries are exported to Revit, and the virtual BIM building module of the existing apartment building is integrated with the modular enhanced envelope system. The result is a detailed model of the renovated apartment building, including modular panel families that can be used in other BIM projects.
8. Quantification of renewable energy production: A parametric simulation is executed for the calculation of renewable electricity produced by the BIPV-panels. Parameters, such as the efficiency of BIPV-panels, soiling, snow coverage, shading, and electricity transformation losses, are calculated for new panels, and after lifetimes of 10 and 20 years.

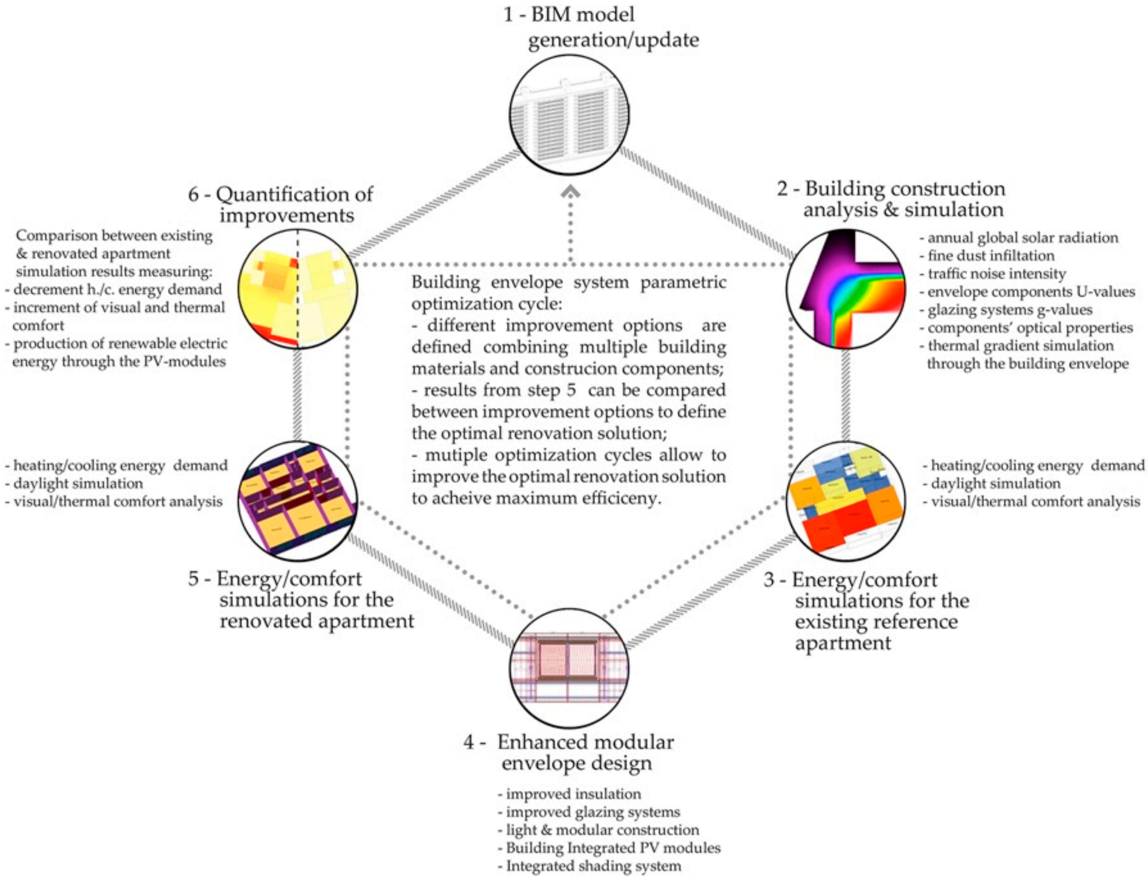

Figure 2. Overview of the Building Information Modeling (BIM)-parametric renovation framework utilized for the development of the sustainable renovation strategy for the exemplary apartment building. The framework is organized in one BIM-model generation/update and five recursive parametric optimization phases.

The integrated BIM-parametric workflow allows the comparison of analysis and simulation results for energy demand, and visual and thermal comfort for multiple renovation variants. Accordingly, the effect of different renovation variants can be simulated depending on the different optical and thermal properties of the utilized materials and construction components of specific building envelope renovation system variants. The BIM-parametric renovation framework allows the improvements to be quantified in terms of the visual and thermal comfort, as well as the heating and cooling energy demand for each renovation option. Improvement results for different options can be compared according to the analyzed parameters. The comparison results facilitate the identification of preferred solutions for the renovation of apartment buildings.

3. Results

3.1. Description and Virtual BIM Reconstruction of the Exisiting Exemplary Apartment

The apartment building selected for the development of the enhanced building envelope system based on the BIM-parametric renovation workflow is a standard, 15-storey high, residential unit located in the Gireum neighborhood of Seoul, located in the Seongbuk district of Seoul. The apartment building analyzed is number 103 (hence called "building 103") included in the Sambu apartment complex, a linear cluster of five apartment buildings constructed in 1992, and located in the middle of the Gireum neighborhood [64] (Figure 3).

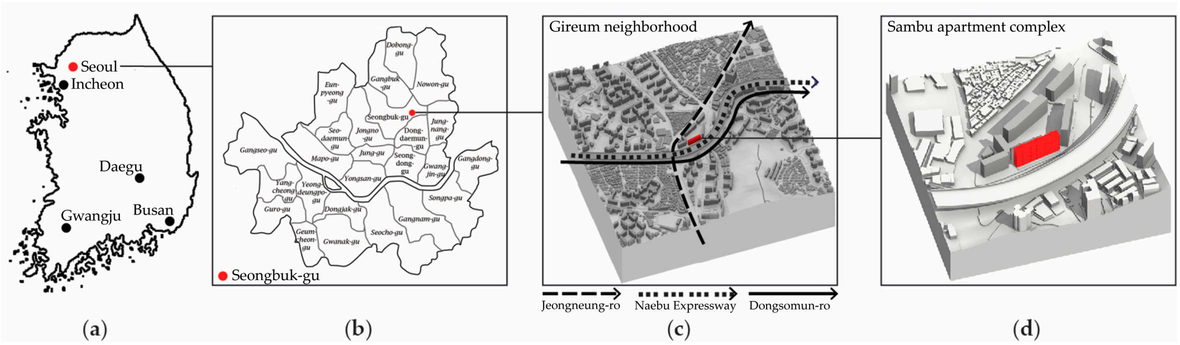

Figure 3. Localization of building 103 in (**a**) South Korea, (**b**) district subdivision of Seoul, (**c**) the Gireum district, and (**d**) the Sambu apartment complex.

Apartment units in building 103 each have a floor plan of approximately 139 m^2 [65] (Figure 4), a standard dimension for apartment units in South Korea. The disposition of four bedrooms around a central area containing the kitchen (on the North) and the living room (on the South) is typical of Korean apartments [66]. The presence of a continuous southern enclosed deck (Figure 5a) is additionally a common feature in apartments in South Korea. On the North, apartments have smaller windows, with a smaller enclosed deck connecting to the bedroom in the Northwest (Figure 5b).

The structural frame of the building in load-bearing reinforced concrete walls is the main construction system in South Korea for apartment buildings. Building 103 has a lifetime of 26 years, which is therefore greater than the average lifespan of apartment buildings in Korea.

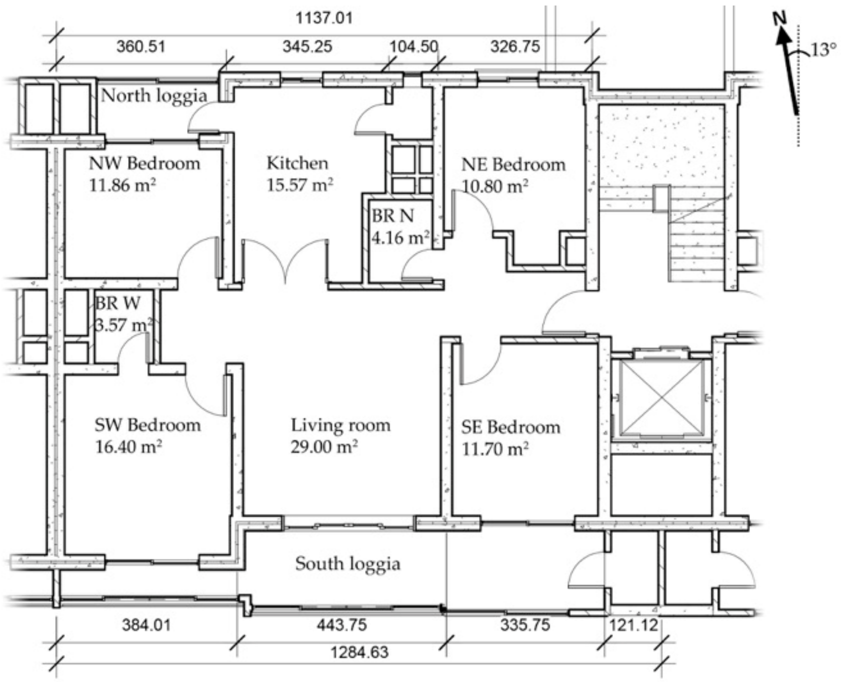

Figure 4. BIM reconstruction of the standard apartment unit in building 103 with indication of each room floor space (left apartment unit in the middle core—dimension annotations in cm).

Figure 5. BIM reconstruction of the standard apartment unit in building 103: (**a**) south façade and (**b**) north façade.

The virtual BIM reconstruction of building 103 has been executed using construction data retrieved from the in situ survey of the building, and literature on the construction of apartment buildings in South Korea [7,66,67]. The construction system of building 103 presents three central elevator–staircase cores integrated into the reinforced concrete load-bearing wall structure. Two apartments units are connected with each core from left and right. The resulting number of apartment units per floor is six, with a total of 90 units for 15 floors. The floor height is 2.50 m with a room height of 2.30 m. The three central cores extend over the building rooftop for two additional floors. The last floor of each central core extension serves as machinery room for the elevator and water supply deposit. The building supporting structure consists in externally insulated load-bearing reinforced concrete walls (load-bearing wall thickness: 250 mm; insulation thickness for the exterior load-being walls with windows: 50 mm polystyrene panels; insulation thickness for roof and side exterior load-bearing walls without windows: 70 mm) [68].

3.2. Simulation of the Thermal and Optical Properties of Window Components in the Exisiting Building

According to the survey of the apartment, window elements are composed of double-glazing and cast iron or aluminum frame construction. For correct simulation of daylight in the reference apartment unit selected, the thermal and optical properties of windows have been simulated. In particular, the light transmission coefficient of windows (g-value) has been defined by observing windows in the existing building and determining the amount of soling, scratches, and maintenance status of each element, depending on the position of each window located on the south- and north-oriented building façades. No windows are included in the West- and east-oriented façades. The average window g-value has been observed to range from 0.50 to 0.75. Southern Enclosed deck windows present an average g-value of 0.65, and are more difficult to clean due to their exterior position and larger surfaces, as well as direct exposure to traffic. The g-value of 0.65 for south-oriented windows has been calculated as the average between the lower g-value of exterior enclosed deck windows (g-value: 0.55), more exposed to external natural (rain and soling) and anthropogenic (traffic smog and particulate of industrial origin) agents, and the windows between the indoor spaces and the enclosed deck (0.75) are more protected from exterior soiling due to their internal position. The average g-value of 0.65 has been additionally defined to account for variations in the maintenance state of windows located in the different apartment units of building 103. Northern windows are more protected from traffic particulate, and present smaller cleaning surfaces. As such, their average g-value has been set at 0.72, considering the presence of a enclosed deck positioned in front of the northwestern bedroom, and the smaller windows in both the northeastern bedroom and the kitchen. To simulate the thermal properties of existing windows, the program WINDOW has been utilized (Figure 6).

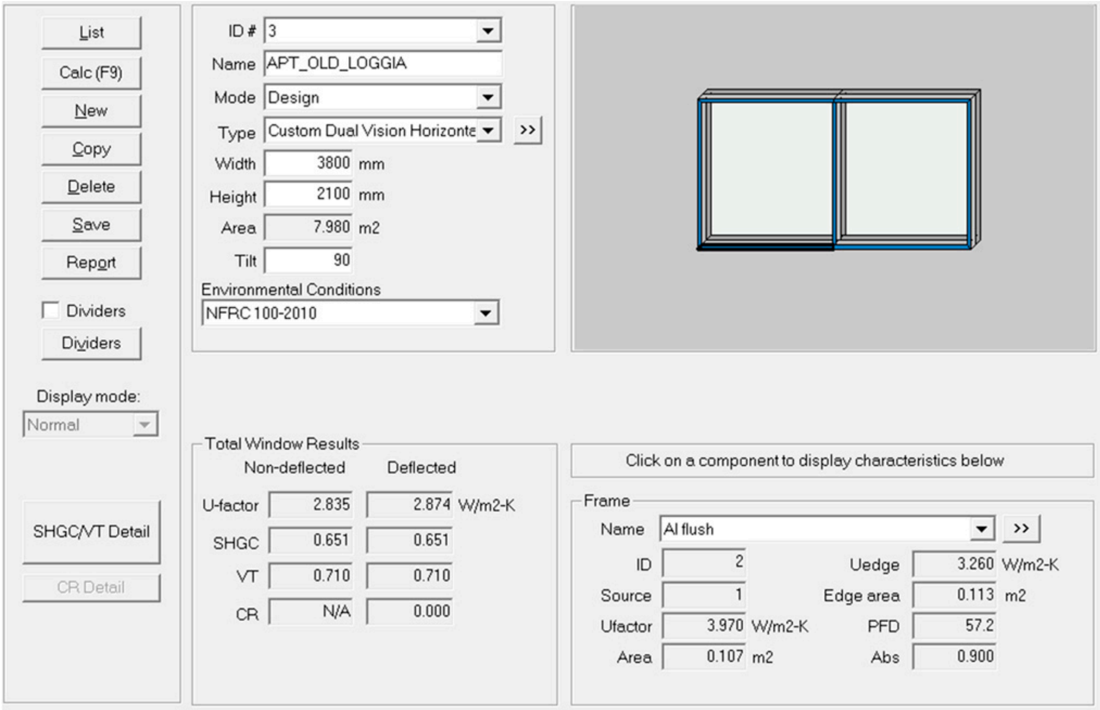

Figure 6. WINDOW simulation of the thermal properties of glazing and frame window construction for the exemplary case of enclosed deck windows.

The construction of windows for the simulation has been defined by calculating the thermal properties for each window element depending on the specific dimensions of each component for a double clear glazing system with aluminum frame. G-value calculations for the windows are consistent with the glazing system adopted in the WINDOW simulations. Table 1 presents an overview of the geometrical, optical, and thermal values calculated for each window type.

Table 1. Different apartment window U-values and g-values.

Window Type	Dimensions (Length × Height in cm)	U-Value (W/m^{2}K)	g-Value
Enclosed deck	380 × 210	3.163	0.65
Glass door	200 × 200	3.224	0.65
Bedroom Southeast	250 × 110	3.019	0.65
Bedroom Northwest	250 × 110	3.019	0.72
Bedroom Northeast	130 × 100	3.153	0.72
Kitchen	90 × 50	3.432	0.72

3.3. Global Radiation Analysis of the Building Envelope and Selection of Reference Apartment Unit for Daylight Simulations

The simulation of daylight has been executed for a single reference apartment unit located in building 103. The reference apartment unit selected is located on the left of the central core of the 7th floor in building 103, at 17 m height. The reference apartment unit has been selected according to the analysis of the cumulative annual solar radiation for the building envelope. Accordingly, the reference apartment unit presents the average annual cumulative solar radiation and direct sunlight hours calculated for all units in the building. Therefore, the daylight simulation of the reference apartment allows estimation of the average natural light access across all units in the building, providing a good approximation of the general visual comfort condition in the building.

Building 103 is oriented 13° from the Southern direction (Figure 7a,b). The Expressway platform and neighboring buildings project shadows on the building façades.

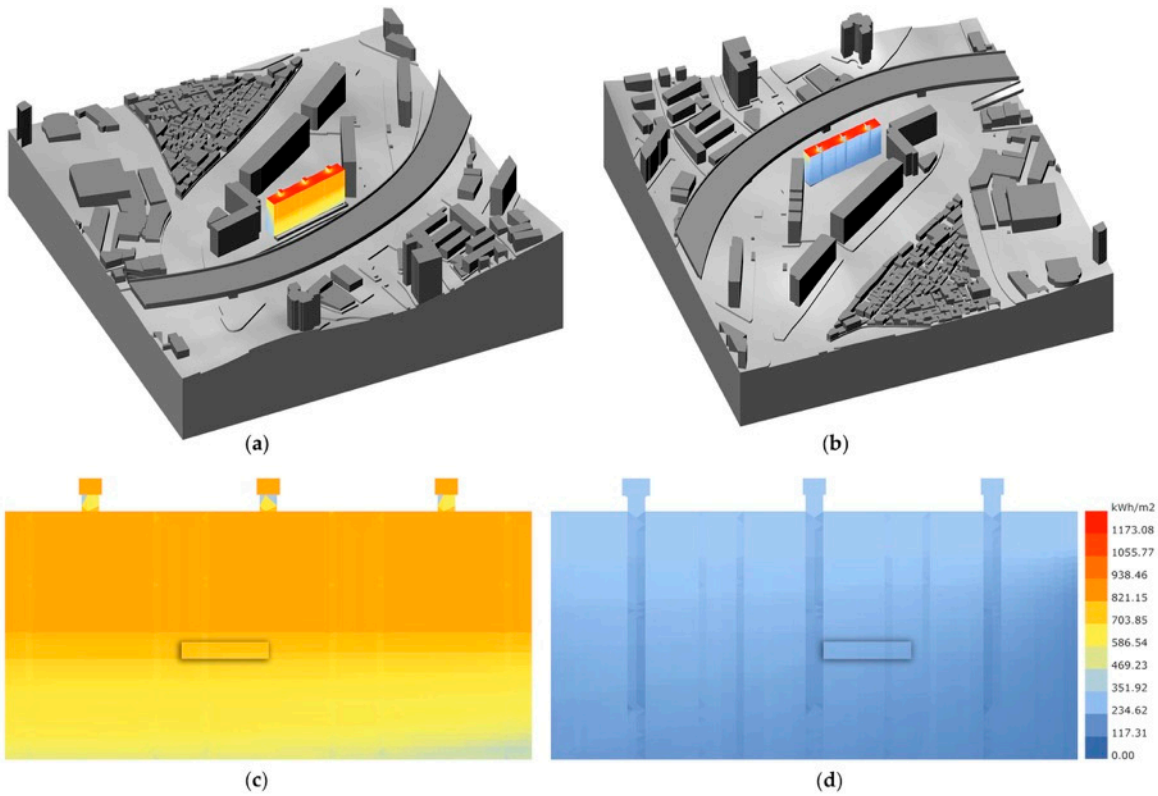

Figure 7. Annual cumulative solar radiation analysis of building 103: (**a**) Solar analysis with contextual shading for the south-oriented façade; (**b**) solar analysis with contextual shading for the north-oriented façade; (**c**) overview of cumulative annual solar radiation for the South-oriented façade and the reference apartment (marked surface); and (**d**) overview of cumulative annual solar radiation for the north-oriented façade and the reference apartment (marked surface).

The cumulative annual solar radiation analysis for building 103 shows an average of 600 kWh/m^2 for the south-oriented façade (Figure 7c), and 300 kWh/m^2 for the north-oriented façade (Figure 7d). Accordingly, the reference apartment unit selected presents average annual cumulative solar radiation values for both south- and north-oriented façades. The analysis of cumulative annual sunlight hours for the reference apartment unit shows in addition an average of 3000 h/a of sunlight for the south-oriented façade and 400 h/a for the north-oriented façade.

3.4. Daylight Simulation of the Existing Reference Apartment

To calculate the amount of exterior radiation being transmitted, reflected, and diffused into the interior spaces of the building, the Daylight Factor (DF) was calculated for a reference apartment in building 103 [69]. The optical properties assigned to the construction materials of the virtual apartment model of the daylight simulation have been taken from the Radiance library for rendering materials, and common optical material properties are available from the online databases [63]. Table 2 lists the optical properties assigned to the interior and exterior component material surfaces of the reference apartment unit. To map both the DF and the Daylight Autonomy (DA) for the reference apartment, the percentages of daylight radiation that were received on a virtual horizontal area, which was positioned 80 cm above the apartment floor surface, were simulated. The simulation of received daylight was based on the division of the virtual horizontal area into a sensor grid with a unit size of 10 cm × 10 cm. The parametric system used a cumulative sky matrix, which was based on the weather data for Seoul. The calculation of the DF was based on the simulation of an overcast sky on 21 September, at 12:00 h (noon).

Table 2. Fractional values for different optical properties of the construction material surfaces of different components.

Component	Red Refl.	Green Refl.	Blue Refl.	Specularity	Roughness
Outdoor façade	0.33	0.33	0.33	0.08	0.18
Indoor ceiling	0.15	0.15	0.15	0.14	0.06
Indoor floor	0.08	0.08	0.08	0.10	0.15
Window frame/door	0.19	0.40	0.19	0.12	0.07

The resulting DF apartment unit floor plan map illustrates the percentage of daylight that was irradiated on the specific indoor areas (Figure 8). According to the *BREEAM* and *DGNB* sustainable building certification systems, a minimum DF of 2% should be available in at least 80% of each room's floor area, in order to fulfill the minimum comfort criteria [70].

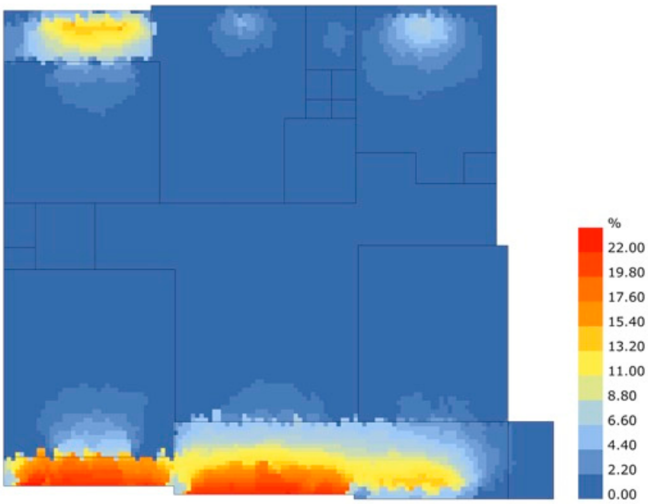

Figure 8. Daylight factor (DF) ground floor map for the reference apartment unit with illustration of the DF in the majority of 0% (dark blue) to 22% (dark red).

The results of the reference apartment unit's daylight analysis illustrated significant differences of the DFs. Table 3 lists the percentages of the total apartment unit area with specific Daylight Factor thresholds.

Table 3. Percentage of total apartment unit area with specific DF thresholds.

Daylight Factor Threshold	Percentage of Total Apartment Unit Area
≥20%	1%
≥15%	3%
≥10%	6%
≥6%	11%
≥2%	21%
<2%	**79%**

In the enclosed deck areas, the DFs were between 11 % and 22 %, while 80% of the indoor area had a DF of less than 2%. The windows between enclosed decks and outdoors and the glass doors between enclosed decks and indoors, as well as shadowing from the apartment units above, significantly reduced the amount of daylight penetrating into the apartment unit. The enclosed deck positioned in front of the northwestern room had a higher average DF of 12%. The kitchen had only a small window, and had a maximum DF of 6% on less than 5% of the room area. The bedroom in the Northeast had a DF of 6% on 27% of the room area. Accordingly, only 20% of the entire apartment unit indoor area met the minimum DF of 2% required for comfortable indoors.

The results of the DA (Figure 9a) show the percentage of hours during the year, when the illuminance values exceed the minimum comfort threshold of 300 lux. Additionally, the Useful Daylight Illuminance (Figure 9b) shows the percentage of hours during one year, when illuminance values are between the minimum value of 300 lux and the maximum threshold of 700 lux. The minimum and maximum illuminance thresholds for visual comfort are defined according to the specific room and residents, including the elderly [42] (Figure 9b).

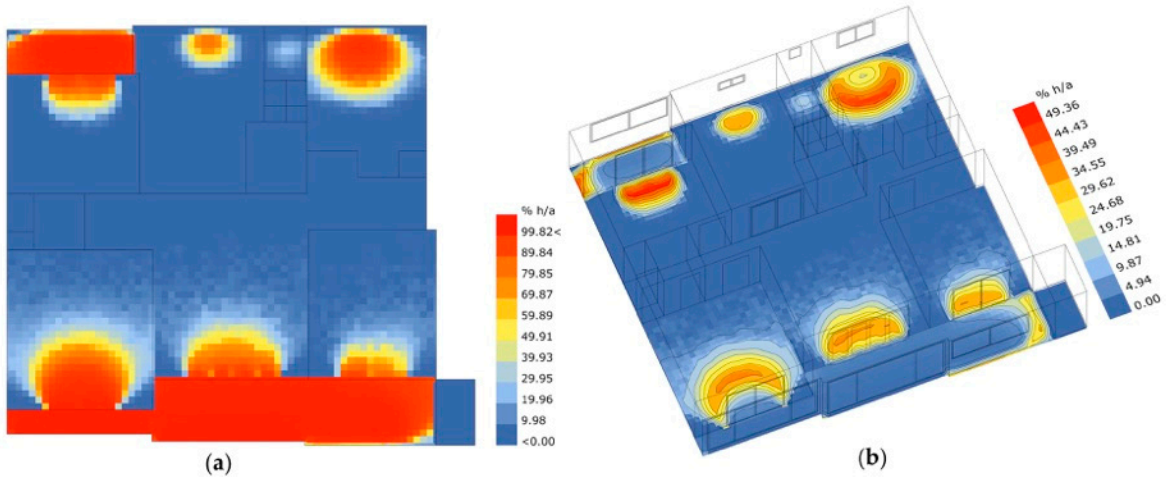

Figure 9. (**a**) Annual Daylight Autonomy (DA) map and (**b**) Useful Daylight Illuminance (UDI) analyses for the reference apartment unit.

Table 4 summarizes the simulation results for the mapping of both the DA and UDI of the reference apartment.

Table 4. Percentage of apartment area for the DA and UDI thresholds.

DA Threshold	Covered Apt. Area	UDI h/year Threshold	Covered Apt. Area
>90%	16.40%	>70%	0.00%
>70%	21.24%	>50%	5.01%
>50%	24.80%	>30%	13.24%
>30%	28.89%	>15%	19.65%
>10%	38.02%	>5%	32.91%

The DA simulation results show that only 16% of the total apartment area received illuminance values of more than 300 lux during 90% of the total annual daylight hours. Only 25% of the total apartment area received minimum comfortable illuminance values for more than 50% of the total annual daylight hours. The areas with the highest amount of hours of minimum acceptable illuminance levels above 300 lux were the enclosed decks. However, the enclosed decks were only infrequently used. As such, the higher daylight levels enjoyed from these spaces present only limited benefit for the occupants of the apartment. Additionally, the UDI analysis showed that the maximum illuminance threshold for residential uses (700 lux) was exceeded in the enclosed decks, reducing the overall visual comfort in these zones. Therefore, only 5% of the apartment unit indoor area had illuminance levels between (300 and 700) lux during more than 50% of total annual daylight hours. South-oriented rooms receive comfortable illuminance levels during 30% of total annual daylight hours on approximately 20% of the total floor area. The UDI measured in the south-oriented rooms was reduced, due to overexposure of the areas near the enclosed decks. Only 18% of the south-oriented cumulated room area met visual comfort criteria during 30% of total annual daylight hours. North-oriented rooms received mostly indirect radiation, which contributed to lower illuminance levels in the comfortable range of (300 to 700) lux. However, due to the comparatively small window areas only 20% of the north-oriented room areas received minimum comfortable illuminance levels of 300 lux. According to the UDI analysis, only 15% of the north-oriented cumulative room area received comfortable illuminance levels in the range (300 to 700) lux, while 5% of the room area had illuminance levels that were above 700 lux.

According to the visual comfort analysis of the existing apartment unit, the following elements influence the daylight distribution in the indoors.

1. Double windows with comparable low g-values contribute to a constant reduction of the incoming solar radiation. The windows reduce the amount of daylight penetrating into the indoors and produce lower visual comfort due to the resulting reduced Daylight Factor. Enclosed deck spaces have a DF of 22%, while indoor zones have an average DF of 1.25%.
2. The enclosed decks are nonconditioned buffer zones with higher amounts of daylight than the conditioned indoors. The DA is 99% for the enclosed deck and 12% for indoor spaces.
3. The WWR is 72% for the south-oriented façade and 15%. As a result, the north-oriented rooms have a lower DA of 12% compared with the south-oriented rooms, which have a DA of 16%.

3.5. Development of the Enhanced Building Envelope Modular System and Improved Apartment Layout

Two strategies have been defined for the in situ sustainable renovation of the reference apartment unit analyzed. The intervention solutions developed for the reference apartment unit can be applied to other apartment units within the building, given the modular structure of building 103, and the repetition of the same apartment unit layout throughout the entire building:

- An enhanced building envelope modular system that integrates increased insulation with lower U-value than for the existing condition, improved window components with lower U-values and higher g-value, Building Integrated Photovoltaic (BIPV) panels, and an exterior shading system. The definition of the enhanced envelope system has been determined on the base of the results of energy and daylight simulations, and the relative visual and thermal comfort simulations executed through the BIM-parametric renovation framework [62].
- The reconfiguration of the existing apartment layout by expanding the interior rooms in the enclosed decks located both on the north and south, as well as the allocation of new storage areas in the existing central zones of the apartment that present reduced daylight (Figure 10).

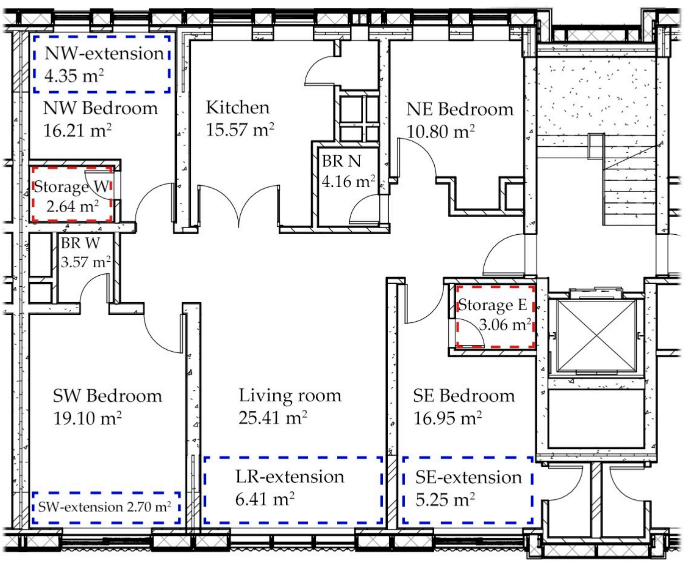

Figure 10. Virtual BIM model of the renovated apartment showing the exterior enhanced building envelope system and the reconfiguration of the interior spaces, with indication of the cumulative floor space of each room and extension/storage areas.

The description of the enhanced envelope panel construction has been developed and published in previous research by the authors [62]. Table 5 provides an overview of the specific construction layers of an exemplary façade module for the enhanced building envelope (Figure 11).

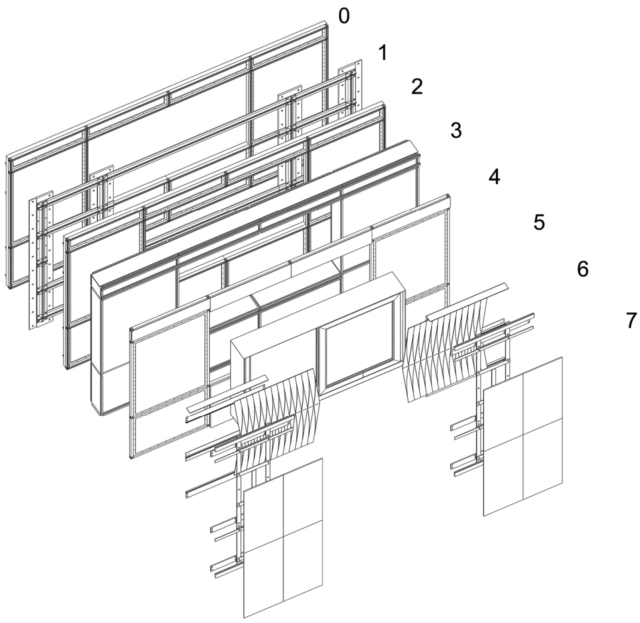

Figure 11. Enhanced building envelope system exemplary façade module. Each layer number is associated with the description provided in Table 5 below.

Table 5. Description of the modular building envelope renovation system construction, with specification of the individual layers from 0 (inside) to 7 (outside), name, component configuration, and layer depth [62].

Layer No.	Name	Component Configuration and Materials	Depth
0	Indoors building envelope layer	Gypsum boards & wood frame	Depth: 8–10 cm
1	Support structure	Stainless steel frames	Depth: 4–6 cm
2	Construction support frame	Timber frame & stainless steel rail connectors to layers 1 & 3	Depth: 6–8 cm
3	Thermal insulation panel	Glass wool [71], timber frame, & aluminium foil (vapor barrier)	Depth: 20 cm
4	Construction support frame	Timber frame, stainless steel connectors, & plastic membrane (waterproof barrier)	Depth: 6–8 cm
5	Window component	Timber frame, double glazing & rubber gasket	Depth: 10–15 cm
6	Solar blind system	Recycled plastic & stainless steel	Depth: 8 cm
7	Mounting System & 1. Cladding 2. Cladding	Stainless steel 1. Glass, plastic film, multicrystalline silicon (PV) & aluminium frame 2. Recycled plastic panels [72]	Depth: 10 cm 1. Depth: 2 cm 2. Depth: 0.5 cm
Σ	Complete component window Complete component 1. cladding 1 Complete component 2. cladding 2	Multiple (see above) Multiple (see above) Multiple (see above)	Depth: 42.5 cm 1. Depth: 55 cm 2. Depth: 43 cm

The integration of the enhanced envelope modular system with the building construction determined specific improvements: an overall reduction of the s of the building envelope increased indoor solar gains due to the higher g-values of the new windows installed as well as the production of renewable electricity through the use of BIPV.

The expansion of indoor spaces in the enclosed decks determined the direct interface of interior apartment rooms with the outdoors. Accordingly, a new WWR has been defined to take into account the direct exposure to natural light, and the increased direct solar gains of indoor spaces. The definition of the new WWR follows both the analysis of annual cumulative solar radiation executed in Section 3.4, as well as studies on window sizing for optimal indoor comfort in residential and nonresidential buildings [73–75]. Accordingly, the average WWR after the renovation of the apartment is 30% for the south-oriented façade (existing WWR: 72%, improvement: −42%) and 18% for the north-oriented façade (existing WWR: 15%, improvement: +3%). Table 6 shows the WWR for each room in the renovated apartment.

Table 6. Window-to-wall ratio of single rooms for the existing and renovated reference apartment unit. The WWR is calculated as the portion of each exterior room surface covered by windows.

Component	WWR (Existing Apartment)	WWR (Renovated Apartment)
Southeast bedroom	38.5% *	28% (−18.5%)
Living room	86.6% *	35% (−51.6%)
Southwest bedroom	86.3% *	28% (−58.3%)
Northwest bedroom	40.2% *	23% (−17.2%)
Kitchen	2.7%	10% (+6.3%)
Northeast bedroom	17.2%	22% (+5.2%)
Building façades WWR improvement (decrease/increase)	WWR (existing apartment)	WWR (renovated apartment)
South-oriented façade	70.46%	30.33% (−40.13%)
North-oriented façade	20.03%	18.33% (−1.70%)

* Double window system (between enclosed decks and the outdoors and closed decks and the indoors).

The difference in terms of WWR between the south- and north-oriented façades depends on the amount of cumulative annual solar radiation received and the balance between solar gains and heat losses through the window glazing for each building façade. Additionally, the construction system developed for the montage of the enhanced envelope panels on the existing building structure differs for the two façades, and influences the dimension of windows in the renovated apartment. On the south-oriented façade, the enhanced building envelope panels replace the enclosed deck exterior walls with no load-bearing function, and can be mounted on a load-bearing structure directly connected to the ground. For the north-oriented façade, the enhanced envelope panels are directly mounted on the existing load-bearing exterior wall through a steel subconstruction. Therefore, the dimensioning of windows for the enhanced building envelope panels on the north-oriented façade has been planned to avoid weakening the structural resistance of the existing load-bearing exterior wall through the construction of new openings in the existing construction. Additionally, the presence of home appliances, plumbing, and fixtures, as well as fixed furniture being placed indoors in front of the north-oriented façade walls in the apartment units, further limited the dimensions of the new window openings. In the kitchen, the presence of fixed fittings considerably reduced the allowed dimension of the additional window included in the exterior building envelope façade panels.

The selection of the appropriate window components for the renovation of the existing apartment has been defined according to three variables:

- Life cycle analysis (LCA) of common window frame materials: The LCA has been employed to select the optimal window frame system material with the lowest environmental impact. The LCA-based selection of window frame components has been made between unplasticized polyvinyl chloride (PVC-U), wood, and aluminum. For the evaluation of the life cycle environmental impact of the window frame materials selected, the DGNB (German: Deutsche Gesellschaft für nachhaltiges Bauen—German council for sustainable building) criteria ENV1.1 (Ecological footprint/balance) and ENV2.1 (Resources utilization) have been utilized (Table 7) [76,77]. Energy and resource utilization data for the different window frame materials have been extracted from the wecobis.de [78] and oekobau.dat [79] databases of the German Ministry for the Interiors, Land and Housing. On the basis of the LCA-based analysis, a wood window frame has been selected for the enhanced building envelope system as the material with the lowest environmental impact.

- Life cycle analysis of current available technologies in South Korea: For the construction of the enhanced building envelope system, a locally produced window system has been selected to reduce the impact of transportation costs and emissions on the life cycle balance of the renovation project. Accordingly, the current window components available on the Korean market have been analyzed. The analysis resulted in the selection of a clear glass double-glazed and wood frame window system for the construction of the enhanced building envelope system modules. To evaluate the thermal performance of the window system selected, a WINDOW simulation for the different windows components installed in the enhanced building envelope modules of the renovated apartment has been conducted. Table 8 presents an overview of the window components installed for each room of the apartment, and their relative U-values and g-value.
- Maximization of solar gains: To improve daylight access and solar gains through the window glass panes, a higher g-value has been defined for the double clear glass window system installed in the enhanced building envelope modules. The g-value of 0.80 has been defined according to data retrieved from the glazing system database of the software WINDOW. As the WWR of the building façades has been slightly increased for the north-oriented façade and substantially decreased for the south-oriented façade, a g-value of 0.8 could be maintained during the entire operative life of the enhanced building envelope panels. The possibility of constantly maintaining the visual performance of the window glass surfaces by preserving the same g-value during the operative life of the components is allowed by the improved access and operation of windows for maintenance purposes defined by comparably smaller cleaning surfaces, the removal of double window systems in the enclosed decks, and protection from soiling provided by the shading system.

Table 7. Life cycle analysis of different window frame material options executed according the DBNG criteria ENV1.1 and ENV2.1. Material data have been extracted from the wecobis.de and oekobau.dat databases of the German Ministry for Interiors, Land and Housing.

DGNB Criteria ENV1.1—Ecological Footprint/Balance						
Material	**Reference Unit**	**GWP (Kg-e CO_2)**	**ODP (Kg-e R11)**	**PCOP (Kg-e C_2H_4)**	**AP (Kg-e SO_2)**	**EP (Kg-e $PO4^{3-}$)**
PVC-U	1.0 m w. frame	9.117	$3.395*10^{-10}$	0.00345	0.0242	0.00290
Wood	1.0 m w. frame	4.02	$2.272*10^{-11}$	0.00350	0.0158	0.00257
Aluminum	1.0 m w. frame	13.27	$1.311*10^{-10}$	0.00346	0.0624	0.00423
GWP (Global Warming Potential); ODP (Ozone Depletion Potential); PCOP (Photochemical Ozone Creation Potential); AP (Acidification Potential); EP (Eutrophication Potential)						
DGNB Criteria ENV2.1—Resources Utilization						
Material	**Reference Unit**	**PEnr (MJ)**	**PEΣ (MJ)**	**PEr (MJ) (% PEΣ)**	**ADP (MJ)**	**WD (m3-equivalent)**
PVC-U	1.0 m w. frame	167.70	183.42	15.72 (8.57%)	155.6	0.0582
Wood	1.0 m w. frame	85.03	146.67	61.64 (42.02%)	71.7	0.0228
Aluminum	1.0 m w. frame	176.1	239.05	62.95 (26.33%)	149.9	0.156
PEnr (Primary energy—non renewable); PEΣ (Primary energy—total); PEr (Primary energy—renewable); ADP (Abiotic resources Depletion Potential); WD (Water Demand)						

Table 8. Overview of the window components installed for each room in the enhanced building envelope system. Figure 11 shows the position of the installed window components in the renovated apartment.

Position	Dimensions (Length × Height cm)	Amount	U-Value (W/m²K)	g-Value
Southeast bedroom	200 × 125	1	1.994	0.8
Living room	90 × 145	3	2.000	0.8
Southwest bedroom	200 × 145	1	1.994	0.8
Northwest bedroom	90 × 125	2	2.025	0.8
Kitchen	90 × 50	2	2.280	0.8
Northeast bedroom	90 × 125	2	2.025	0.8

Figure 12 presents an overview of the south-oriented (Figure 12a) and north-oriented (Figure 12b) façades of the reference apartment unit after renovation.

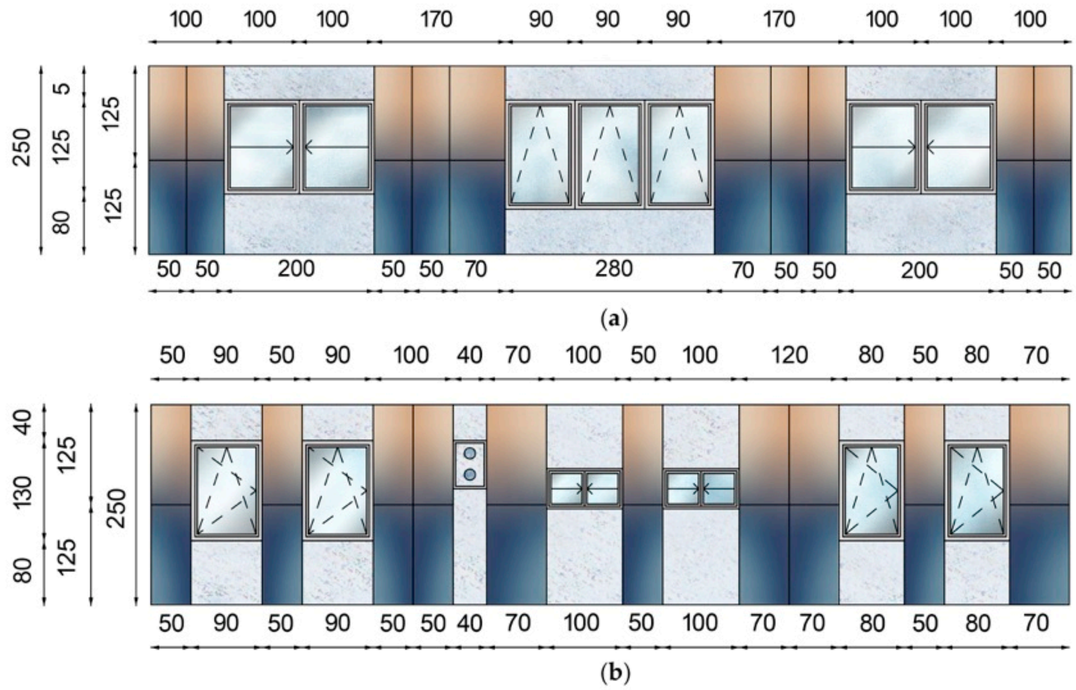

Figure 12. Enhanced building envelope system mounted on (**a**) south-oriented façade and (**b**) north-oriented façade (measures in cm).

3.6. Daylight Simulation of the Renovated Reference Apartment Unit

Figure 13 shows the grid-based (grid spacing 10 cm × 10 cm, grid height 80 cm) DF simulation of the renovated apartment floor plan (Figure 13) with improved room layout and building envelope. According to the selection of improved construction components, the g-value of windows was improved from 0.65 in the south facade and 0.72 in the north façade to a g-value of 0.8. Construction optical properties (RGB reflection, Specularity, and Roughness) remained unaltered, in order to facilitate the quantification of improvements related to the new WWR, improved g-value, and position of windows and room extensions.

Table 9 compares the quantification of daylight improvements between the DF analysis for the existing and renovated reference apartment units. Compared to the existing condition, the renovated reference apartment unit shows an overall increase of the DF by 15%. Additionally, both southwestern and southeastern bedrooms reach the minimum DF threshold of 2%, for a minimum of 80% of floor space, defined by the international sustainable building certification systems *BREEAM* and *DGNB*. The remaining rooms, with the sole exception of the kitchen, reach a DF of 2% for an average of 30% of the cumulative room surface, which presents an increase of 23% compared to the existing condition. The kitchen shows a limited increase of 11% area exposed to a minimum DF of 2%, due to the remaining low WWR of 10%. However, improved WWRs and increased g-values successfully contribute to the generally better DF in all rooms of the apartment unit. The direct solar access of the rooms extended into the enclosed deck spaces also increases the amount of daylight received in the apartment unit.

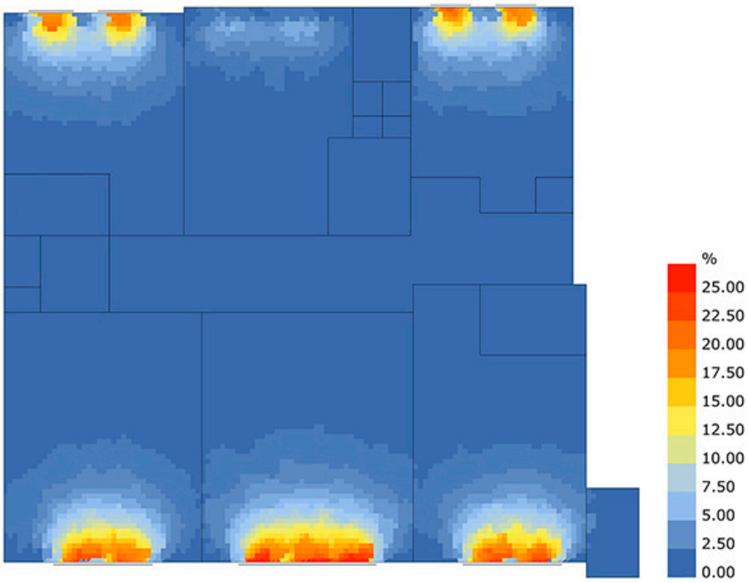

Figure 13. Grid-based daylight factor (DF) analysis from 0% (dark blue) to 25% (dark red).

The analysis of DA (Figure 14a) shows an overall average increase of 30% apartment surface exposed to illuminance values exceeding 300 lux for at least 50% of the yearly hours. The southeastern bedroom and the living room have significantly improved DAs, with approximately 48% and 63% room surface area exceeding the minimum threshold of 300 lux for 50% of annual hours. North-oriented rooms show a lower increase in DA, with an average 20% of additional room surface receiving minimum illuminance levels during 50% of the year.

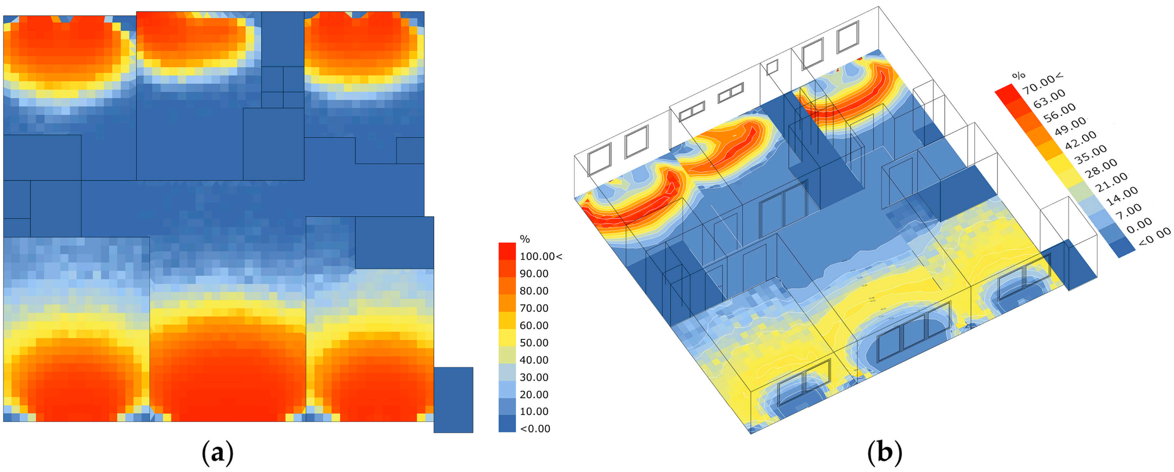

Figure 14. Reference apartment annual grid-based daylight autonomy (DA) and useful daylight illuminance (UDI) analyses; (**a**) DA analysis of the apartment unit's floor plan from 0% (dark blue) to 100% (dark red); (**b**) UDI analysis of the isometric apartment floor plan layout from 0% (dark blue) to 70% (dark red).

Table 9. Daylight factor analysis comparison between existing and renovated apartment units, with quantification of improvement for single rooms (percentage of room area exceeding specific DF thresholds) and room surface ratios of optimized versus existing situations.

Apartment Room (DF Threshold)	Optimized Daylight-Factor (% Room Area for DF Threshold)	Existing Daylight-Factor (% Room Area for DF Threshold)	Improvement (% Room Area for DF Threshold)	Room Surface Ratio (Renovated/Existing)
Room SE				
≥20%	1.90	0.00	+1.90	1.15
≥10%	8.91	0.00	+8.91	
≥5%	20.79	0.00	+20.79	
≥2%	87.46	3.40	+84.06	
Living room				
≥20%	2.71	0.00	+2.71	1.22
≥10%	9.19	0.00	+9.19	
≥5%	16.04	0.00	+16.04	
≥2%	32.61	2.09	+30.52	
Room SW				
≥20%	0.10	0.00	+0.10	1.15
≥10%	7.75	0.00	+7.75	
≥5%	16.80	3.08	+13.72	
≥2%	82.25	10.93	+72.72	
Room NW				
≥20%	1.02	0.0	+1.02	1.13
≥10%	6.54	0.0	+6.54	
≥5%	16.30	0.0	+16.30	
≥2%	34.75	7.03	+33.72	
Kitchen				
≥20%	0.0	0.0	0.0	1.00
≥10%	0.0	0.0	0.0	
≥5%	0.45	0.0	+0.45	
≥2%	15.03	3.95	+11.08	
Room NE				
≥20%	0.41	0.0	+0.41	1.00
≥10%	6.21	0.0	+6.21	
≥5%	17.71	3.32	+13.39	
≥2%	37.08	18.45	+18.63	

The calculation of the UDI included the utilization of the external solar blind system to reduce excessive daylighting. The daylight simulation calculated the shading of natural light for solar blinds installed exclusively in the south- and north-oriented bedrooms of the renovated apartment unit, according to daylight control requirements for mixed-use spaces (resting, working, and so on). Solar blinds are not considered to be installed in the enhanced building envelope panels positioned in front of the kitchen and the living room. Table 10 summarizes the construction and operation specifics of the solar blind system utilized for the daylight simulation model.

To define the impact of solar blind closing degrees on the amount of sunlight penetrating into the reference apartment unit for the daylight simulation, the Bidirectional Scattering Distribution Function (BSDF) material definition method [80] was used. The BSDF (Figure 15a,b) material definition method allows the simulation of internally and externally transmitted, reflected, and diffused sunlight through windows equipped with specific solar blind systems. The grid-based UDI analysis of the reference apartment unit (Figure 14b) illustrates the improvement in daylight control due to the use of the external solar blind system in all four bedrooms. The kitchen did not require external shading, due to the small window dimensions and WWR. The living room is equipped with a light internal shading system with a solar transmittance of 0.85 because the vertical tilt opening mechanism of the windows did not allow manual operation of the external blinds.

Table 10. Construction and operation specifics of the solar blind system defined for south- and north-oriented bedrooms for the daylighting simulation.

Construction Specifics of the Shading Blind System	Operation Conditions
Type and orientation: External vertical blinds Thickness: 0.55 mm Solar Reflectance: 0.65; Solar Transmittance: 0; Emittance: 0.9 Conductivity: 221 W/mK Distance from glass exterior surface: 0.12 cm Single shade dimensions (l × h cm): 12 × 125	Four conditional operative states for illuminance values above 700 lux 1. Completely opened (retracted blinds) 2. 20° rotation South orientation (slightly closed—Figure 15a) 3. 50° rotation South orientation (partially closed—Figure 15b) 4. 80° rotation South orientation (completely closed) The simulation program progresses from condition 1 (completely open) to condition 4 (completely closed) until illuminance levels measured by a sensor positioned 1.20 m from the center of the window(s) at 1 m height are lower or equal to 700 lux.

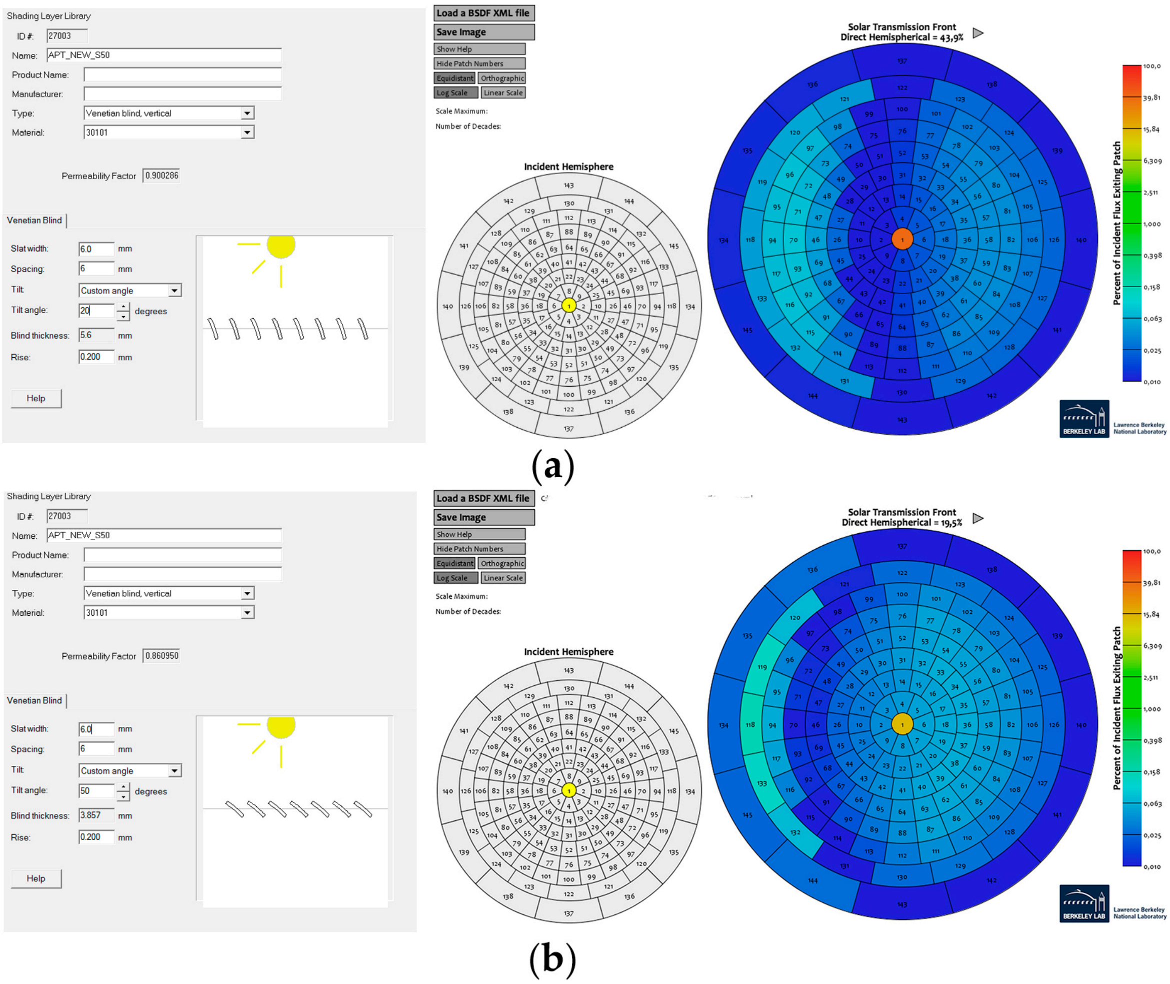

Figure 15. (Left) WINDOW-generated BSDF-based shading position for (**a**) 20° orientation (2-slightly closed condition) and (**b**) 50° orientation (3-partially closed). (Right) BSDF solar transmission hemispherical sky map for (**a**) 20° orientation (2-slightly closed condition) and (**b**) 50° orientation (3-partially closed), visualized with the Radiance-developed BSDFviewer.

The UDI analysis of the renovated apartment unit shows differences in the acceptable illuminance levels in south and north-oriented rooms. Direct exposure to sunlight increased both illuminance levels and exposed floor space in the south-oriented rooms, improving the useful daylight illumination. However, if the cumulative amount of floor space that was exposed to acceptable daylight values per year was increased, illuminance levels in south-oriented rooms also more frequently exceeded the maximum illuminance threshold of 700 lux. Twenty-five percent of the floor area in south-oriented rooms received acceptable levels of illuminance for 30% of the annual hours.

High levels of illuminance reduced the room area exposed to a minimum of 50% of comfortable annual hours in the southeastern bedroom by 5.30%, and in the southwestern bedroom by 8.30%. Thirteen percent of the north-oriented room floor area received comfortable and acceptable levels of illuminance for 30% of the annual hours.

However, the average amount of annual hours with acceptable illuminance levels within all apartment unit rooms was increased after renovation. On average, 6% additional floor area was exposed to a minimum of 50% of acceptable hours.

Different UDI values between south and north-oriented rooms were caused by the influence of the improved WWR on the amount of light penetrating into the indoors, and the illuminance values measured in the single rooms. Direct daylight penetration into the south-oriented rooms results in a bigger floor area with higher illuminance levels, which often exceed the acceptable daylight intensity threshold of 700 lux. In the north-oriented rooms, indirect solar gains through smaller windows result in a lower increase of illuminance values for a higher amount of comfort hours per year, on a smaller portion of the room area. Therefore, northern rooms enjoy better illuminance values for a longer time during the year, but for a smaller area, than the south-oriented rooms.

Table 11 summarizes the overall increase of DA and UDI for each apartment unit room before and after the renovation in percentages for specific DA and UDI thresholds. Furthermore, the table lists the number of hours per year when the use of shading systems facilitates the reduction of uncomfortable illuminance levels to comfortable illuminance levels for each room.

Table 11. Daylight autonomy and useful daylight illuminance analysis comparison between existing and renovated apartment units and daylight improvement quantification for single apartment rooms (percentage of room surface exceeding specific DA/UDI thresholds).

Room (DA/UDI Threshold)	DA—Existing (% of Room Area for Threshold Value)	DA—Renovated (% of Room Area for Threshold Value)	DA—Renovated (% of Room Area for Threshold Value)	UDI—Existing (% of Room Area for Threshold Value)	UDI—Renovated (% of Room Area for Threshold Value)	UDI Improvement (% of Room Area for Threshold Value)	Comfort Hours Added with Blinds (300 < ill < 700)
Room SE							
≥80%	2.64	25.82	+23.18	0.00	0.00	0.00	768
≥50%	8.52	48.64	+40.12	5.29	0.00	−5.29	
≥30%	12.94	71.47	+58.53	11.76	34.53	+22.77	
≥10%	24.41	88.58	+64.17	23.23	80.48	+57.25	
Living room							
≥80%	7.14	44.01	+36.87	0.00	0.00	0.00	N.A.
≥50%	14.76	63.15	+48.39	8.33	8.37	+0.04	
≥30%	20.00	75.11	+55.11	18.88	42.34	+23.46	
≥10%	37.14	93.30	+56.16	36.42	74.40	+37.98	
Room SW							
≥80%	15.47	21.20	+5.73	0.00	0.00	0.00	720
≥50%	24.28	44.20	+19.92	8.33	0.00	*−8.33*	
≥30%	30.27	63.60	+23.27	23.09	33.40	+10.31	
≥10%	59.71	95.20	+35.49	53.33	88.00	+34.67	
Room NW							
≥80%	5.90	21.78	+15.80	0.00	0.00	0.00	432
≥50%	12.84	37.62	+24.78	12.84	17.82	+4.98	
≥30%	16.31	48.51	+32.20	16.31	35.64	+19.33	
≥10%	21.18	58.74	+37.56	21.18	55.11	+33.93	
Kitchen							
≥80%	0.00	14.41	+14.41	0.00	0.00	0.00	N.A.
≥50%	3.84	26.68	+22.84	2.88	10.42	+7.54	
≥30%	6.00	33.12	+27.12	6.00	23.31	+17.31	
≥10%	9.13	42.33	+33.20	9.13	39.26	+30.13	
Room NE							
≥80%	11.81	23.90	+12.90	0.00	0.0	0.00	312
≥50%	21.32	40.74	+19.42	14.40	21.88	+7.48	
≥30%	30.83	48.82	+17.99	30.83	35.69	+4.86	
≥10%	42.36	57.23	14.87	42.07	53.87	+11.8	

According to the visual comfort analysis of the existing apartment unit, the following elements influence the optimized daylight distribution indoors.

1. Luminosity levels are increased, compared with the existing apartment unit, due to the removal of enclosed decks. The increase of illuminance in certain areas of the apartment can be regarded as more comfortable than the reduced daylight in the indoors of the apartment unit before renovation. Shading systems can be operated to reduce the amount of light penetrating into the apartment.
2. The introduction of shading systems causes a substantial reduction of excessive daylight levels in the south-oriented spaces. However, shading of daylight in the immediate vicinity of the outdoors from the indoors provides zones located more distantly from windows with reduced daylight. Accordingly, the available daylight autonomy for interior apartment unit zones is lower.

The WWR of the south-oriented and north-oriented façades has been decreased by 40.13% and 1.70%, respectively. The UDI of the south-oriented façade has increased due to the higher penetration of daylight into the adjacent rooms. The main reasons are the extension of the rooms into the originally enclosed deck area and reduction of glass layers by replacement of the double window systems by a single window. Excessive illuminance values have decreased due to reduced WWR. The overall daylight access of the north-oriented rooms has also increased due to the extension of the northwest bedroom and the increased WWR of kitchen and northeast bedroom facades by 10% and 22%. The amount of floor space covered by sufficient daylight for at least 50% of annual hours has increased by approximately 7%. Furthermore, the maximum threshold for the amount of annual hours measuring comfortable daylight levels has increased from 50% to 70% of annual comfortable hours.

4. Discussion

The simulation of daylight for the renovation of the reference apartment unit in building 103 accurately describes the influence of the spatial configuration of the standard apartment unit layout on the internal distribution of natural light in Korean apartment buildings. Buffer zones, such as enclosed decks, greatly influence the cumulative daylight access of indoor spaces in apartment building in South Korea. Additionally, the daylight simulations allow potential dependencies to be determined between the varying level of natural lighting in the indoor areas of the apartment and the type, as well as the frequency, of different activities performed in the apartment rooms. Furthermore, the daylight analysis presented in this research provides the assessment of visual comfort in Korean apartment units according to specific illuminance thresholds based on international standards. As such, the assessment of visual comfort for apartment units in South Korea can be compared with other building typologies in the same country or abroad, and act as a benchmark in the evaluation of daylight for a wide range of similar buildings.

Three main measures for the increase of acceptable daylight levels in the indoors of apartment units have been identified in this research: (i) removal of buffer zones (enclosed decks) between the indoors and the outdoors, (ii) improvement of the WWR, and (iii) installation of window components with higher g-values. Among the three measures, the increase of g-values (iii) has the highest influence on the penetration of daylight into the rooms. The removal of buffer zones (i) and the improvement of the WWR (ii) facilitate a better indoors light distribution and solar access.

A relevant aspect in the calculation and simulation of daylighting is the reduction of overall UDI in apartment unit spaces by operation of shading devices. The daylight simulation described in Section 3.6 includes the operation of dynamic shading systems for the reduction of excessive illuminance levels. The reduction of illuminance by the different orientation of movable blinds is based on measurements of one sensor in each room located at a fixed distance from the facade. By operation of the shading system, the entire room space is affected by the reduction of illuminance values. Accordingly, interior zones with greater distance from windows do not receive minimum illuminance threshold values set for daylight comfort. Therefore, apartment units with shading systems could have similar average

UDI values as units without shading systems. Interior zones in apartment units without shading system would receive higher illuminance levels and would compensate the excessive illuminance levels in areas near windows. Accordingly, the introduction of shading systems in apartment buildings benefits greatly the indoor visual comfort of occupants. Occupants can regulate the amount of daylight penetrating into the rooms by manual operation of the shading system.

The daylight simulation executed for the existing reference apartment unit condition provides consistent data for the definition of visual comfort improvement strategies through the development of the enhanced building envelope system. Results are based on the daylight simulation of a reference apartment unit receiving comparably average sunlight radiation levels throughout the year. Therefore, the installation of specific window components in the enhanced envelope system panels provides improvements in terms of DA and UDI for a broad range of apartment unit conditions, and these improvements do not exclusively apply to the reference apartment unit analyzed. The solution developed for the reference apartment unit is therefore a standard renovation strategy providing average improvements of DF, DA, and UDI. Accordingly, the application of the standard renovation solution to other apartment units can result in higher or lower visual comfort improvements, depending on the position and condition of each apartment unit within the building.

A refined process aimed at the development of specific daylight improvement solutions that varies according to the position of each apartment unit within the building and its condition can consistently influence the monetary cost and lifecycle of panel components in the enhanced building envelope system. The required space for the installation of improved window components in the enhanced building envelope panels can be reduced for apartment units that present higher cumulative annual solar exposure. The reduction of WWR for specific apartment units allows, on the one hand, the saving of monetary costs for the installation of windows and, on the other hand, increased surface of PV modules and production of renewable electric energy. Costs and efficiency of the components defining the enhanced building envelope system can therefore be optimized to further improve the economic and technological feasibility of in situ renovation strategies for apartment buildings. The BIM-parametric renovation framework is purposely defined to include the definition of individual local solutions, and could support the detailed planning of renovation projects for apartment buildings.

The development of specific visual comfort improvement solutions tailored to individual apartment units can be realized through a parametric system that takes into account local variations in terms of the position of each apartment unit in an apartment building and its condition. However, the number of control parameters involved in the definition of individual solutions increases with the level of the detail required in the daylight analysis. Aside from the previously described simulation parameters related to the apartment unit layout, construction, and size of window components, factors such as the varying maintenance degree of components, amount and source of soiling, as well as operative schedules of windows for each apartment unit can further influence the complexity of daylight simulations. To determine realistic simulation and calculation values for the additional control parameters, a dedicated analysis of each additional factor has to be conducted either for each building to be renovated, or using data retrieved from the analysis of a statistically significant pool of apartment buildings. The analysis process of each parameter allows understanding of the dependencies between external or internal agents and local variations (such as the shading determined by neighboring structures) in terms of window components conditions. External agents influencing the visual comfort in apartment building can be defined by particulate matter of natural or anthropogenic nature, soiling due to rainwater runoff on window surfaces, and so on. Internal agents influencing indoor visual comfort can be represented by operative schedules, damage, and scratches from utilization of the windows. However, previous research efforts have not yet concentrated on detecting the specific dynamics and dependencies between external/internal agents and indoor daylight conditions. Furthermore, statistical data on the use and condition of window components in apartment buildings in South Korea has not yet been produced, and will be an object of further research from the authors. The parametric analysis of daylight based on local conditions can define a valid improvement in terms of enhancing daylight and visual comfort increase. The simulation of daylight for apartment units based on local internal/external agents defines an alternative daylight analysis and improvement system. The parametric daylight analysis system is an alternative to statistical learning techniques based on building usage data and user behavioral analysis. A preliminary heuristic analysis method could therefore be developed to assess window component conditions for the specific case of building 103, so as to detect potential dynamics between external/internal agents and local variations in terms of daylight.

Dynamics and specific factors affecting the propagation and distribution of natural light in indoor spaces also provide a model for the analysis of deterioration and maintenance of window components during their life cycle, after the completion of the apartment building renovation. The daylight simulations presented in this research calculate daylight for an average g-value of 0.8, which is a standard value determined by taking into account the eventual deterioration of glass panes in window components, and the relative reduction light transmission due to soiling. However, a more detailed analysis of the causes for the reduction of window g-value during the operative life of the components would allow a more precise, detailed, and realistic quantification of the effective amount of light penetrating through windows in a determined life span. Accordingly, a lifecycle oriented simulation of daylight is under development for the further improvement of this research.

A detailed definition of internal/external agents and parameters influencing daylight in apartment units can additionally contribute to a more accurate model for the dynamic control of solar blinds, and improve daylight measurements in indoor spaces. As such, an increased number of rotational states for solar blinds defined through the BSDF method could refine the daylight simulation model and improve the quantification of the efficiency of the shading system through a more sensible control of natural light filtration into indoor spaces.

The development of the enhanced building envelope system depends on the available window components and glazing technologies in South Korea. However, the usage of local components provides a limited choice in terms of available systems, as well as lower thermal and optical performance of the selected windows, if compared with products available on the international market. Accordingly, the comparative life cycle analysis between alternative products on the international market and the locally available window components can provide a better outlook on the trade-off between monetary costs, the environmental impact of outsourced production and transportation of window systems, and the increased energy and thermal and visual comfort performance of improved window components.

Aside from the development of a heuristic model for the definition of parameters influencing the simulation of window conditions and daylighting, the cultural approach towards natural light and its control in Korean living spaces must also be addressed. Empirical observations show that dwellers, as well as workers in offices and public spaces in South Korea, tend to prefer artificial constant light to varying natural daylight. Accordingly, the standard apartment layout, with enclosed decks serving as buffer zones for natural light filtration, could be explained by the general tendencies of the Korean living culture to prefer more stable illumination sources, and avoidance of external sunlight as the main lighting source. Therefore, the definition of an improved apartment unit layout and the enhanced building envelope system should take into account preferences from dwellers, and could bring about consistent variations from a renovation model based only on international standards for visual comfort. The presence of buffer zones could therefore be integrated into indoor spaces, and a new spatial configuration could provide the benefits in terms of natural light filtration sought by Korean apartment dwellers, as well as improved visual comfort requirements from international standards and reduced artificial lighting energy demand.

5. Conclusions

The research discussed in this study focuses on the improvement of daylight for the renovation of an aged reference apartment building through a BIM-parametric framework. The research shows that the renovation of an exemplary apartment building through the parametric definition of the improved apartment unit spatial layout and the installation of the enhanced building envelope system provides an increase of 15% for Daylight Factor, 30% for Daylight Autonomy, and 15% for Useful Daylight illuminance, compared to the existing apartment unit condition. The parametric definition of construction specifics and optical properties of window components, as well as the dynamic simulation of integrated shading systems, allow correlation of the variable construction properties of alternative products with improvements in terms of daylight and visual comfort, to select the best fitting window components for the renovation of apartment units. Accordingly, the research proves the efficacy of the BIM-parametric renovation framework to successfully develop in situ, sustainable renovation strategies for aged buildings, aimed at improving indoor visual comfort. The optimization and development process of renovation solutions through the BIM-parametric renovation workflow could therefore be adopted exclusively for the renovation of window systems in aged buildings, and be applied in a wider range of partial refurbishment projects both in South Korea and Asia alike. Further research work will address the modeling of external/internal agents in the indoor daylight simulation for apartment units and the assessment of their impact on the visual comfort of apartment building occupants. Additionally, the impact on indoor visual comfort produced by the deterioration of transparent and semi-opaque components during their entire life cycle will be analyzed. External and internal agents influencing component deterioration will be identified and included in the daylight simulation model. Successively, improvements in terms of daylighting produced by the replacement of existing windows with components with better optical performance will be quantified. The research will concentrate on comparing the performance and environmental impact of components produced in South Korea and foreign countries. The trade-off in terms of environmental impact of components' life cycle between local and imported window components will be assessed. The assessment of components' performance and life cycle impact will define a method to develop sustainable solutions for renovation projects of aged buildings.

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