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What is This?
Development of a Double-Skin Façade for Sustainable Renovation of Old Residential Buildings

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Key Words
Double-skin · Renovation · Façade design · Sustainable building · Building energy

Abstract
The modernist movement in architecture has led to a building boom of a large number of high-rise buildings with glazed façades. These façades were aesthetically pleasing, but have a high energy loading. To address this, a double-skin façade (DSF) has been proposed to manage the interaction between the outdoor and indoor environments. A DSF can contribute to balance the demand for energy saving, thermal and visual comfort, and a high-tech image for building envelopes. The design of the DSF involves decisions on geometric parameters, glass selection, ventilation strategy, shading, daylighting, aesthetics, wind loads, and maintenance and cleaning cost expectations. This paper reports an experimental application of a DSF in an old apartment building which has been modelled in order to find the configuration to select design parameters that could minimize the energy demand and total carbon emissions. A simulation-based virtual environment program was used to determine the optimal sustainable features of the double-skin envelope. Results of the simulation are presented and discussed for four different cavity widths and ventilation modes of operation, highlighting the potential savings in comparison to the existing façade construction. The impact of internal shading within cavity space was also investigated.

Introduction
The modernist movement in architecture has led to a building boom of a large number of high-rise buildings with glazed façades. These façades were aesthetically pleasing but could increase the energy load of buildings. The demand for energy saving, thermal and visual comfort, and a high-tech image for new building envelopes can be met with a double-skin facéd (DSF) system, which is widely encouraged, proposed, and increasingly designed by architects. A number of interesting investigations and findings are reported in literature on ventilation and thermal performance of DSFs [1–4], which has conclusively shown that a DSF could be optimally the best...
option to manage the interaction between the outdoor and indoor environments.

The ecological footprint concept demands that architects, designers, and contractors should turn away from large-scale redevelopment projects and focus instead more towards individual renovation to save construction resources at low costs. In Korea, the government has subsidized refurbishment projects for any apartment complex built more than 20 years ago. Korea has seen a rapid growth in the market for renovated or refurbished apartments in the past few years. Recently, there has been a drive to revise the housing law to require the use of sustainable technology for refurbished apartments, with the aim of energy conservation in buildings. Heat gain via heat transfer through windows is one of the major thermal loads in a building envelope. As a solution, environmental control integrated with façade design has been recognized as an important and useful strategy in terms of energy-efficient building renovation.

Implementation of DSFs in existing buildings has seen broad application in recent years. This paper reports an experimental application of DSF in an old apartment building which was modelled and studied in order to find the configuration to select design parameters that would minimize the energy demand and total carbon emissions arising from building operation. A simulation-based virtual environment (VE) program was used to perform a fully automated search aimed at finding the optimal values for the double-skin envelope features. The results of the simulation are presented and discussed for four different cavity widths and ventilation modes of operation, highlighting the potential savings in comparison to a standard façade construction. Finally, the impact of internal shading devices within a cavity space was also investigated, and the directions for future development of a DSF configuration to facilitate wider acceptance of the built-in shading device are suggested.

**Sustainable Features of a DSF**

Due to increased interest in the sustainability of the built environment, DSF recently has been receiving much attention. Naturally, a ventilated DSF seems very interesting from an energy point of view, but good design and a proper operation of the system are crucial to improve the energy saving. The design of the DSF would involve consideration of factors such as geometric parameters, glass selection, ventilation strategy, shading, daylighting, aesthetics, wind loads, and maintenance and cleaning cost expectations. Seok et al. [6] proposed a method for a simple design process that would consider the interactions between many of these design parameters. His results showed that the most significant parameters (in terms of the total energy load) are building orientation, cavity height, cavity depth, blinds position, outer skin U-value, and inner skin U-value. He also found that the interaction between cavity depth and aperture size was important.

The intermediate cavity space is a particularly promising aspect of a DSF. This cavity space can serve as a natural solar collector and a buffer to prevent overheating with properly-operated ventilation. By using the cavity, solar energy can be efficiently gathered using the movement of air. Chan et al. [7] investigated the energy performance of DSF applied to a typical office building. Their work showed that a DSF system with single clear glazing for the inner pane and double reflective glazing for the outer pane can result in an annual building cooling energy saving of around 26%, as compared to a conventional façade with single absorptive glazing. Additionally, Pasut and Carli [8] showed, through a sensitivity analysis, a good strategy for carrying out a computational fluid dynamics simulation of this type of building envelope.

In addition to collecting solar energy, a DSF can also aid ventilation of a building, which can lead to significant energy saving. Most of the strategies to enhance ventilation use the concept of the stack effect, through the DSF. The performance of the DSF would depend heavily on the chosen ventilation means within its intermediate cavity space. Wong et al. [9] analyzed various thermal comfort parameters (for a building in a hot and humid climate) with different double façade configurations to determine the best natural ventilation strategies for high-rise buildings. Sælens et al. [10] described how to optimize the energy performance of single-story multiple-skin façades, in terms of the net energy demand, by changing the operating modes of the façades and the HVAC system. They found that control strategies for the airflow rate and recovery rate of the air could lead to significant improvements in the heating and cooling loads.

Jiru and Haghighat [11] presented a zonal approach for modelling airflow and temperature in ventilated DSFs. They found that both increasing the height of the DSF and installing venetian blinds would increase the inlet-outlet temperature difference, but an increase in the airflow rate would cause the difference to decrease. Kuznik et al. [12] also used a zonal approach to investigate the mass transfer based on the pressure difference in a numerical model of a DSF. The simulation was validated using a full-scale DSF.
experimentally studied in a summer configuration with different airflow rates and different angles of the solar shading devices. The proper positioning of these shading devices is obviously additionally important in glare control and maximization of day lighting.

Silva and Gomes [13] also moved beyond computational simulations and conducted a set of wind tunnel tests over a multi-storey building model with different DSF layouts. They used a range of wind directions to examine configurations such as open on all edges and fully lateral closure and from narrow to wide gap depths. The results demonstrated a layout-dependent inner wall pressure distribution (which may be considerably different from that found for an unsheltered building). Mingotti et al. [4] also looked at a multi-storey building, and investigated the natural ventilation of a DSF with a vertically distributed heat source (analogous to a shading blind/louvers heated by solar radiation) connected to a room with a horizontally-distributed heat source (such as would be found in an underfloor heating system [14]). They showed how the height of the façade and the size of the openings can affect the preheating of the room in colder seasons, as well as to prevent overheating in warmer seasons. As in the work of Silva and Gomes, the model was validated using laboratory experiments [13].

Høseggen et al. [15] examined the effect of a DSF in a predominantly cold climate. They focused on a planned office building in the city-centre of Trondheim, Norway, and examined whether a DSF applied to the east façade would reduce the heating demand enough to make the DSF a profitable investment. While they found that the economic payback was not sufficient for that case study, the work did describe how a DSF with controllable windows and hatches for natural ventilation can be implemented in the simulation program. Kim et al. [16] also examined the economic impact of natural ventilation on the heating load and energy cost in a building with a southwest-facing DSF. They found that controlling the natural airflow rates from the cavity space to the indoor space could effectively reduce heating loads due to the accumulation of solar irradiance. Hashemi et al. [17] monitored a building with a DSF in a hot and arid climate, in order to observe the behaviour of the façade in both hot and cold conditions. It was found that while the temperature difference between the outer skin, the inner skin, and the cavity can significantly save heating energy in winter, additional operating modes are needed to reduce the cooling loads in summer. The suggested techniques included night ventilation and installation of shading devices for the cavity. Perez et al. [18] looked at a dry Mediterranean climate, and developed a classification system for the incorporation of green vertical systems into a façade, with a focus on the microclimate that can be created between a wall and the green curtain.

Baldinelli looked at a glass DSF, also in a warm climate in the Mediterranean region (central Italy) [19]. The DSF was equipped with integrated movable shading devices, and the model incorporated the optics of the materials, the fluid dynamics of the DSF, and the building energy balance. He found building cooling requirements are reduced in the summer, since the external part of the façade would absorb most of the solar heating, such that there is no significant influence on the inner skin and on the internal environment.

Beyond energy saving, a DSF can also increase occupant comfort. Huckemann et al. [20] compared the individual sensory perception of the indoor environment with the actually measured indoor climate (including factors such as temperature and humidity) in buildings with double-skin and single-skin façades. They found that buildings with a DSF have a slight advantage over single-skin façades in terms of thermal comfort.

Research Design and Methodology

Analysis Tools

The method used in this study was to model an old apartment building with and without a DSF on the south face and then compare the energy demand and thermal environment for various alternatives. For this purpose, computer models could be easily built and tested for variety of design alternatives to find the best option. There have been questions whether several whole-building simulation tools can accurately describe the transient heat and mass transfer phenomena that occur in the complex three-dimensional geometry of a DSF. Kim described an empirical validation of the computer simulation tool for performance simulation of a DSF [21].

Due to its capabilities and interface options, IES_VE (Virtual Environment) was chosen as the building energy simulation program to be integrated with the various third-party applications. VE is an easy-to-use software tool for the design and analysis of building systems which are required to provide acceptable energy efficiency and thermal solutions. It was selected to be used in this research to model the renovation of an old residential building with an attached DSF through the optimization of the appropriate cavity configuration and the width of the intermediate space.
The basic model configuration of the building with a DSF was generated using ModelIT, and the annual impact of the glazed wall on the amount of energy consumption was analyzed. Apache-sim calculated the heating and cooling load in the process of the energy analysis. Finally, the Suncast module of IES_VE was able to predict solar shading.

**Computer Model Construction**

With the aim of overcoming the energy consumption problem in old buildings, a new DSF structure covering five storeys was developed. A DSF in an old apartment house consists of an external glass surface, a shading system, a gap filled with air, and an insulating double internal glazing system, integrated with opaque walls. As shown in Figure 1, the five-storey apartment house module was constructed in VE with the geometrical dimensions of $16.1 \times 11.5 \times 2.3 \, \text{m}$, with $2.3 \, \text{m}$ ceiling height (about $152 \, \text{m}^2$ of floor surface area in total).

The south façade was renovated with a DSF. The DSF of the model has external and internal panes, with 6-mm thick glass used for the external pane and 6/12/6-mm double glazing used for the inner pane (Figure 2). Simulations were generated for a residential building with the DSF exposed towards the southern direction in the central Korean peninsula. The properties of some of the important building materials are given in Table 1.

**Simulation Boundary Condition and Research Variables**

Intermediate Cavity Width

For the DSF in residential buildings, a total of four different widths of the cavity gap were selected: 30, 60, 90, and 120 cm, as shown in Figure 3. The cavity was expected to play a positive role as a thermal buffer zone for the living spaces, lessening the heating and cooling load.

Shading Device

The analyzed DSF consists of an external layer made of an integrated glass-shading device system, making it possible to take advantage of the benefits of DSFs in winter conditions as well as the cooling load reduction derived from the shading system in the summer.

During the heating season, the shading system should be horizontal: a large amount of solar radiation can pass through the façade because the low altitude of the sun above the horizon allows a direct gain, together with an indirect contribution linked to multiple reflections of the slat surface constituting the shading system. In the cooling season, to avoid overheating and discomfort, the shading

![Fig. 1. Unit model geometry of the five-storey residential building. (a) Section of DSF and (b) Intermediate cavity of DSF. DSF: double-skin façade.](image-url)
device should be adjusted with a high tilt angle, stopping the solar radiation.

For the alternative with DSF, as illustrated in Figure 4, a venetian blind constituted of aluminium slats was placed within the intermediate cavity space. The sizes for the blind slats of the DSF system used are 10 cm, 20 cm, and 30 cm. Typical of the DSF was evaluated with a fixed horizontal slat. Generally, shading devices are primarily associated with hot and warm seasons, and, therefore, the energy simulation focused on the investigation of the cooling energy in the horizontal blind system with various slat widths.

Shape of the Double-Skin Cavity

By using the cavity of the double-skin as a thermal buffer, further savings may be achieved. A functional shape to activate more natural ventilation is an effective option in managing the interaction between the outdoors and the internal spaces. Except the conventional base case, a total of 5 different configurations of the double-skin cavity were suggested as shown in Figure 5.

For restitution of a buoyancy force through induced flow inside the gap, the lower part of the DSF in the first floor was eliminated, and this area was completely opened for ventilation purposes. A traditional shape for a DSF can develop a water leak problem when it rains. As a solution to prevent this, a rectangular-shaped cavity was suggested which is called scooped.

Simulation Conditions

Simulation conditions for VE program are tabulated in Table 2. Based on recommendations by the Korean...
government, the internal temperature at the building was set at 20°C to simulate a heating load and at 26°C for cooling load calculation annually. For ventilation as a major constant, the standard value of 0.7 ACH was applied for the building energy simulation. The weather data provided by Korea Meteorological Administration was used.

### Table 1. Thermal property of the model building for virtual environment (VE) simulation

<table>
<thead>
<tr>
<th>Construction</th>
<th>Description</th>
<th>U-value (W m⁻²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exposed floor</td>
<td>Concrete (180 mm) + bid-insulation (65 mm) + cellular-concrete (40 mm)</td>
<td>0.41</td>
</tr>
<tr>
<td>Ceiling</td>
<td>Concrete (180 mm) + bid-insulation (65 mm) + cellular-concrete (40 mm)</td>
<td>0.41</td>
</tr>
<tr>
<td>Internal petition</td>
<td>Plaster (13 mm) + brick (105 mm) + plaster (11 mm)</td>
<td>1.69</td>
</tr>
<tr>
<td>External wall</td>
<td>Concrete (200 mm) + bid-insulation (75 mm)</td>
<td>0.39</td>
</tr>
<tr>
<td>External glazing</td>
<td>Clear glass (6 mm + 6 mm) double layers</td>
<td>1.46</td>
</tr>
<tr>
<td>Double-skin glazing</td>
<td>Clear glass (6 mm + 6 mm) single layer</td>
<td>2.74</td>
</tr>
<tr>
<td>Shading device</td>
<td>Aluminum</td>
<td>5.88</td>
</tr>
</tbody>
</table>

**Fig. 3.** Intermediate cavity width options. (a) 30-cm cavity, (b) 60-cm cavity, (c) 90-cm cavity, (d) 120-cm cavity.

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*Sustainable Performance of DSF in Renovation*

Thermal Performance with Cavity Width

The thermal performance of a DSF depends on the material properties and geometric configuration. The influence of the gap between the outer and inner glass wall on the thermal behaviour might be one of the most important factors in the determination of the amount of heating and cooling.
cooling load. Computer simulations on year-round heating and cooling of the older residential building were carried out using meteorological weather data in Korea.

Figure 6 shows the advantage of the DSF in reduction of the heating and cooling demand. The energy simulation provides a comparison of the annual cooling energy of various DSF configurations with the intermediate cavity widths. As indicated, the double-skin cases with a cavity achieved a comparatively lower reduction in annual cooling energy, ranging from 3% (30 cm) to 40% (90 cm). A similar pattern of heating energy savings was found from the cases in which the reductions range from 2% (30 cm) up to 43% (120 cm). This was mainly caused by the better thermal insulation property of the double-skin glazing located as the outer pane of the original façade.

In the DSF system with an intermediate cavity, it can be seen that the case with a 90-cm-wide cavity performs better. The case with a 60-cm-wide cavity offers a reduction of annual cooling energy of 37%, as compared to the old apartment building with the conventional façade. For the case with a 90-cm-wide cavity, its annual cooling energy was 40% less than the original case. However, as revealed from Figure 6, the percentage of cooling energy saving from DSF case with a 120-cm-wide cavity (21%) was not significantly higher than the case with a 90-cm-wide cavity (40%), even though the cavity becomes much wider. With appropriate design with a 90-cm-wide cavity, a total energy savings 38% could be gained in annual heating and cooling, as compared to a base case building.

Thermal Performance with Shading Devices

Particular attention has also been given to shading systems: different solutions were proposed from louvers to blinds [22,23]. The positive energy savings that were found with a DSF with a 90 cm cavity width brought us to the next stage of the modelling, shading devices.

The built-in shading device within the cavity noticeably attenuates the cooling load. Three different depths of horizontal louver, 10, 20, and 30 cm, were selected to find the most appropriate configuration of shading device for a DSF with the cavity width of 90 cm. As expected, the 30 cm blind slat has the lowest overall heating and cooling energy demand.

As illustrated in Figure 7, the double-skin cases with shading devices comparatively lowered the annual cooling energy, ranging from 46% (10 cm) to 47% (30 cm), as compared to the old apartment building with the conventional façade. Similar patterns of heating energy savings were found from the cases in which the saving percentages range from 23% (10 cm) up to 26% (30 cm).

Comparing the 90-cm-wide double-skin case without a shading device, annual savings in cooling energy of 10%, 11%, and 13% resulted from the cases of a 10-cm-wide, 20-cm-wide, and 30-cm-wide louver, respectively.

Thermal Performance with Cavity Shape

As discussed above, a downside to implementing the traditional configuration of DSF is that a top-opening DSF can lead to a water leak problem; however, adding a roof-covered scoop for certain geometries would give a sufficient solution to this problem and increase buoyancy force in intermediate space. By applying various shapes for this alternative, the achieved energy saving was nearly equal to that of the conventional DSF on an annual basis.

Figure 8 shows the comparison of annual cooling and heating energy of various cavity configurations in
Table 2. Virtual environment boundary conditions

<table>
<thead>
<tr>
<th>Boundary conditions</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design temperature</td>
<td>Cooling set-point 26°C</td>
</tr>
<tr>
<td></td>
<td>Heating set-point 20°C</td>
</tr>
<tr>
<td>Use schedule</td>
<td>All-days</td>
</tr>
<tr>
<td>Air change rate</td>
<td>0.7ACH</td>
</tr>
<tr>
<td>Location</td>
<td>Seoul, Korea (latitude:37°, longitude:127°)</td>
</tr>
<tr>
<td>Weather data</td>
<td>Korea Meteorology Administration</td>
</tr>
</tbody>
</table>

Fig. 5. Shape of cavity space in the double-skin façade (DSF). (a) Base, (b) pilotied, (c) closed, (d) opened, (e) shaded, (f) scooped.
the DSF. The simulation results indicate that the heating energy demand was about 7% lower for the single-skin façade with the closed alternative configuration of DSF solution compared to the traditional DSF. A similar pattern of cooling energy savings was found from the case in which the saving percentages range up to 3%. For the case with the scoop, better savings in cooling energy could be achieved. Saving percentages from 1% in cooling up to 4% in heating were obtained from this scoop case.

**CO2 Emission with DSF**

CO2 emission evaluation is an essential process for a performance assessment of a DSF system. The amount of consumed energy for heating and cooling the building can be characterized in terms of the CO2 emission, as shown in Table 3. Similar trends were found for the cases described above in terms of the CO2 emission. The annual amount of CO2 emissions by applying the developed DSF to the older building is given in Table 3. The saved amount of CO2 emissions could be

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**Fig. 6.** Annual thermal performance with different cavity widths.

**Fig. 7.** Annual thermal performance with different shading devices.
significant in realizing the pragmatic sustainability of the DSF.

Conclusion

In this study, an older apartment building with a DSF was modelled, and its energy performance was predicted with various cavity configurations and shadings. The final goal of the research was to look into the thermal consequences of implementing a DSF in a five-storey residential apartment building with various DSF configurations.

The results showed that over the course of an entire year, the DSF proposed for the older residential building has significantly improved the building energy behaviour, especially when the appropriate width of cavity configuration was considered. It was found that a 90-cm-wide cavity space can provide good thermal performance. A saving in annual heating and cooling energy up to around 38% can be achieved, as compared to a base case building. From a balanced point of view between energy performance and additional capital cost, the double-skin case with a 60-cm-wide cavity would be considered as a feasible option for application in Korea.

A further energy analysis of a DSF equipped with a shading device showed good performance both in winter conditions as well as in the warm season, with a saving in required energy of up to 51% as compared to a base case building. The result underlined the positive effect of the optical property of slats: the high reflective shading device would allow a sufficient amount of solar gain for the indoor space in the heating season, and a considerable cooling load reduction in summer.

Furthermore, alternatives to the traditional DSF format were examined, in order to reduce potential water leakage problems. By applying various shapes in the double-skin cavity, the achieved energy saving was nearly equal to that of the conventional DSF on an annual basis.

Table 3. CO₂ emissions (tons) with double-skin façade (DSF)

<table>
<thead>
<tr>
<th>Cases</th>
<th>CO₂ emissions for heating load</th>
<th>CO₂ emissions for cooling load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original building (base model)</td>
<td>22.0</td>
<td>11.6</td>
</tr>
<tr>
<td>Double skin cavity (30 cm)</td>
<td>21.7</td>
<td>11.2</td>
</tr>
<tr>
<td>Double skin cavity (60 cm)</td>
<td>14.4</td>
<td>7.3</td>
</tr>
<tr>
<td>Double skin cavity (90 cm)</td>
<td>13.9</td>
<td>7.0</td>
</tr>
<tr>
<td>Double skin cavity (120 cm)</td>
<td>12.7</td>
<td>9.1</td>
</tr>
<tr>
<td>Piloti without first floor cavity</td>
<td>13.3</td>
<td>7.2</td>
</tr>
<tr>
<td>Closed cavity (90 cm)</td>
<td>12.9</td>
<td>6.8</td>
</tr>
<tr>
<td>with shading device 10 cm</td>
<td>10.7</td>
<td>6.3</td>
</tr>
<tr>
<td>with shading device 20 cm</td>
<td>10.7</td>
<td>6.2</td>
</tr>
<tr>
<td>with shading device 30 cm</td>
<td>10.3</td>
<td>6.1</td>
</tr>
<tr>
<td>Double skin cavity (90 cm) + scoop</td>
<td>13.3</td>
<td>6.9</td>
</tr>
</tbody>
</table>

CO₂ emissions for electric energy production: 422 g kWh⁻¹ [24].
In terms of CO₂ emissions, the application of the DSF system was found to be environmental-sustainably feasible in Korea. These findings are of the utmost importance as an indicator of whether a DSF would really be possible for use as a means to introduce a sustainable feature to older apartment buildings in Korea. Promotion, motivation and support from the government can foster successful and widespread application of the DSF system in old apartment buildings.

Future work should deal with the extension of the analysis to different locations, with the variation of geometric parameters such as building height, opening for ventilation, the shading shape, and tilt. It would be also useful to analyze the effect of the façade in the daylighting of inner rooms, since a DSF equipped with the fixed shading system might not be desirable for a deep interior.

Acknowledgement

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References