The Impact of Dynamic Envelope Control Strategies on the Building's Smart Readiness Indicator Score and Its Performance.

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Abstract

The Smart Readiness Indicator (SRI) was developed to evaluate buildings' smartness. This study evaluates how varying functionality levels of dynamic envelope smart services impact the building's SRI score and energy performance. An office building located in London underwent both SRI assessment and energy simulation. Results revealed that changing the functionality levels of dynamic envelope services from the lowest to the highest resulted in only a 4.1% increase in the SRI score. Overall, the findings suggest a lack of significant correlation between the SRI score and the building's energy performance. The variation in the energy performance can be notably more pronounced than the alteration in the SRI score, or the adjustment in the SRI score may not necessarily induce a change in the building's energy performance.

Keywords Smart building, Smart Readiness Indicator, Control strategies, Building energy performance.

1.0 Introduction

According to the Energy Performance of Buildings Directive (EPBD) (1), the building stock accounts for approximately 40% of the total energy consumption and 36% of the overall greenhouse gas emissions within the European Union (EU). The EU has set a paramount objective for the year 2050, which involves reducing carbon emissions to levels below those recorded in 1990 by 80%. Given the significant role that the building sector plays in energy consumption and carbon emissions across Europe, it is crucial to actively explore new methodologies and advanced technologies to reduce energy consumption in this sector. Smart buildings could make a considerable impact on achieving this particular aim.

The Technical Committee 247 of the European Standardization Organization acknowledged the importance of focusing on smart buildings. Consequently, they initiated a project aimed at developing a series of standards to define the smartness of buildings. The EN 15232 standard, introduced in 2008, established a systematic approach for categorizing the intelligence of building automation and control systems (2). This standard underwent revision and was subsequently replaced by the EN ISO 52120 standard in 2022 (3).

In 2018, the European Commission adopted the Smart Readiness Indicator (SRI), which draws from the principles outlined in the 15232 standard. The SRI is designed to evaluate a building's capacity to enhance energy efficiency and overall operational performance while accommodating occupants' needs and responding to signals from the energy grid (1). The nine distinct domains have been defined encompassing heating, domestic hot water, cooling, controlled ventilation, lighting, dynamic building envelope, electricity, electric vehicle charging, and monitoring and control. In total, these domains include 54 smart-ready services, and each of these services is evaluated based on seven impact criteria including energy savings on-site, maintenance and fault prediction, comfort, convenience, Well-being and health, Information to occupants, and flexibility for the grid and storage. Each individual service is capable of obtaining a specific score in seven impact criteria based on its functionality level. Services that have a higher functionality level are considered to be smarter in their implementation and consequently tend to offer more benefits to building users or to the grid.

The assessment framework of the SRI calculates a building's score by considering various weighting factors for domains and impact criteria. These weightings differ depending on the building's type and location. Additionally, users have the option to define custom weighting factors. The overall building SRI score is a percentage that denotes how close (or far) the examined building is from the maximum achievable score. The determination of the maximum smart readiness does not necessarily involve assessing all 54 smart-ready services. The SRI methodology employs a triage process, allowing the exclusion of a service from evaluation if it is not applicable to the specific building. As a result, this service is disregarded in calculating the maximum achievable score.

The assessment framework presents detailed and simplified methods to offer flexibility in the evaluation process. Although both methods share a similar structure, the Simplified Method (A) employs a reduced set of services, requiring less effort and expertise to conduct the assessment. It was designed primarily for small buildings of low complexity, such as single-family homes. On the other hand, the Detailed Method (B) is intended for buildings with higher complexity, typically large non-residential buildings, and large multi-family homes.

While utilizing SRI can be advantageous for evaluating a building's smartness, it is important to note that this assessment scheme evaluates buildings based on the presence of various smart services and their corresponding control strategies. Nevertheless, the impact of these smart services on building performance, as well as the impact of architectural design on these services' effectiveness, is not directly addressed in the scheme. Consequently, this study aims to investigate the correlation between smart services, architectural design, and building energy performance, focusing specifically on the smart services associated with the building envelope. To achieve this aim, two primary questions were addressed: First, how does the modification of the control systems of the movable building envelope impact a building's smartness, as measured by SRI, and its overall energy performance? Second, what is the correlation between building design and the effectiveness of these smart services?

To investigate the study's questions, an office building was selected as a case study and subjected to a comprehensive SRI assessment. During this process, the SRI assessment methodology was evaluated. Furthermore, Different control strategies were developed for movable shading devices and window operations, which were subsequently applied in the building energy simulation. These alterations in control strategies facilitated an examination of their subsequent impact on both the SRI score and the overall building performance.

2.0 Literature Review

As a recently introduced rating scheme, several studies have tried to examine the methodological framework established for SRI. These studies explore how alterations in input data, the selection of technical domains, and adjustments in weighting factors can impact the SRI scores. Vigna et al. (4) applied the SRI to assess an office building in Bolzano, Italy, aiming to investigate the level of uncertainty within the SRI assessment system. This evaluation involved two distinct expert groups. The resulting SRI scores from these groups exhibited a 13% variation, emphasizing that the assessor's interpretation and data sources significantly influence the accuracy of SRI evaluation outcomes. Athanasaki and Tsikaloudaki (5) evaluated the impact of technical domain selection and their respective weightings on the SRI score of a single-family residential building in Greece. The findings of the study demonstrate that the inclusion of different technical domains and the utilization of varying weighting factors yield disparate SRI scores. Notably, a higher number of technical domains considered in the calculation corresponded to a lower SRI score. Janhunen et al. (6) highlighted that this ability to choose technical domains and smart services within the SRI methodology can result in non-comparability among the SRI scores of different buildings. Varsami and Burman (7) utilized both the detailed and simplified methods of the SRI to assess the SRI scores of two non-residential buildings in the UK. Their findings indicate that the simplified method yielded higher SRI score results compared to the detailed method. The findings from these studies illustrate the sensitivity of the final SRI score to the degree of freedom considered within the SRI assessment framework for selecting technical domains and changing the weighting factors. Hence, it is crucial to examine more how these parameters can affect the final score.

Moreover, certain studies have explored the relationship between a building's SRI score and its performance by examining various Key Performance Indicators (KPIs). Fokaides et al. (8) evaluated the SRI score of a mixed-use building in Cyprus. In addition, they employed the Energy Assessment tool to determine the building's Energy Performance Certificate (EPC). The findings indicate that despite the building's relatively good SRI score (52%), it received an energy class of D on its EPC, implying that the building's actual energy performance is not aligned with its smartness. Ramezani et al. (9) evaluated the SRI calculation methodology on two buildings located in a Mediterranean climate. They investigated the correlation between each building's SRI score, its indoor environmental quality (IEQ), and energy consumption. The results indicate that the building with a higher SRI exhibited better indoor air quality and lower heating and cooling loads.

Becchio et al. (10) conducted a study to examine the effects of altering shading devices, their controlling strategies, and the open/closed control of windows in an office building in Turin, Italy. The findings revealed that the building's cooling demand and SRI score do not always align. The study indicated that the SRI score is not sensitive to variations in cooling demand associated with different solar shading options (e.g., interior shading, between glass shading, exterior shading). Plienaitis et al. (11) investigated the influence of installing thermostatic radiator valves on the SRI score and heating energy consumption of an educational building in Lithuania. The study findings indicate that the replacement of radiator valves can result in a 10% to 22% reduction in heating energy consumption during different months. Additionally, the SRI score increased from 26% to 29%. According to the findings of these studies, there isn't always a direct correlation between a building's performance and its SRI score. This underscores the necessity of integrating performance-based metrics alongside the SRI score for a more thorough building assessment or when making decisions about smart services. A summary of studies conducted on SRI has been presented in Table 1.

3.0 Case Study Building

The case study building (White Collar Factory) is a commercial office building in central London that was completed in 2017 (Figure 1). Comprising fifteen office levels, along with the ground floor and a basement level, the development includes a total net internal area spanning approximately 22,000 sqm. The architectural layout is an open office plan, with two service and circulation cores.

To ensure thermal comfort, the building utilizes an innovative cooling system that involves circulating chilled water through concrete slabs, thereby transforming the structural elements to function as a radiant cooling source. Additionally, heating is done through trenches positioned along the perimeter of the layout. These systems are supported by the mechanical air system, which brings fresh air to the internal spaces.

Figure 1 Case study building (White Collar Factory), © Tim Soar.

Paper	Location	Building Type	Scenarios	Changing Items	SRI Method	KPI	Results
(4)	Italy	Office	SRI assessment by two expert groups	-	Detailed	-	Each group obtained different results.
(12)	Italy	Residential	The SRI of typical residential buildings and two retrofitting scenarios	All Domains	Detailed	-	The SRI is relatively low in the scenario that represents the current trend of existing building retrofits
(8)	Cyprus	Mixed-use	Comparing the building SRI and EPC	-	Not specified	CO_2 equivalent emissions	The building's actual energy performance is not aligned with its smartness.
(9)	Portugal	Office and laboratory	Comparing the SRI score, energy performance and IAQ of two case study building	-	Detailed	IEQ – heating and cooling loads	The building with a higher SRI has better indoor air quality and lower heating and cooling loads.
(7)	UK	Non-residential	Comparing detailed and simplified methods and the effect of changing weighting factors based on EPC on SRI score.	Suggestions based on optimization and consideration of all domains	Detailed Simplified	Weighting factors based on EPC and DEC	The simplified method provided more SRI score results compared to the detailed approach. Software upgrades and non-invasive measures can lead to a 20% increase in the SRI score of an existing building.
(5)	Greece	Single family residential building	Effect of selecting different technical domains and weighting factors on SRI score.	-	Simplified	Weighting factors based on primary energy consumption.	The number of technical domains and weighting factors have an impact on the final SRI score. The smaller number of technical domains, the higher the SRI score.
(6)	Finland	Educational and office buildings	Effect of selecting different technical domains and the applicability of the SRI to cold climate countries in Northern Europe.	-	Detailed	-	The SRI in its current form is not able to recognize the specific features of advanced district heating (DH) systems. The difference in the number of technical domains can result in different scores.
(10)	Italy	Office building	Effect of changing building shading system, its control, and control of windows on SRI score and cooling demand.	Shading devices – Open/close of the windows	Detailed	Cooling demand	Changes in the building's energy performance and SRI score are not always aligned.
(11)	Lithuania	Educational building	Effect of installing radiator valves with thermostatic heads on SRI score and heating demand.	Radiator valves	Detailed	Heating energy consumption	The energy performance of buildings is closely linked to the level of automation and control systems implemented in the building's technical systems.
(13)	Five EU countries	Residential building	Retrofitting the buildings towards Nearly Zero Energy Building (NZEB) and Positive Energy Building (PEB).	Heating, Ventilation, DHW, Generation/ Storage, Building Automation.	Detailed Simplified	Retrofitting cost	Buildings constructed after the implementation of EPBD in the EU are suitable for implementing certain interventions with relatively low costs, leading to significant improvements in the SRI scores.

Table 1 Summary of the studies that have been conducted on Smart Readiness Indicator (SRI).

In the building envelope design, the glazing area has been intentionally reduced in facades that are exposed to direct sunlight, in contrast to the northern facades. Additionally, occupants have control over window openings and they are guided by a traffic light system to manage the windows. Due to the substantial depth of the building layout, providing fresh air to all areas through natural ventilation is not feasible. Consequently, the mechanical ventilation system has been divided into two components: central and perimeter. The perimeter section relates to the zones with a 6-meter offset from the external walls. According to a predefined condition, windows can be opened when the outdoor temperature falls within the range of 15 to 24 °C. During this period, the mechanical ventilation system serving perimeter areas is deactivated, enabling natural ventilation through the windows.

4.0 Methodology

To accomplish the building's SRI assessment, the SRI version 4.5 calculation sheet was employed (14). Based on the type and size of the building, the Detailed method was adopted, including 54 distinct services. Throughout this investigation, the predefined weights specified within the SRI framework for non-residential buildings located in the Western European climate zone were employed (Table 2).

Domains	**Impact Criteria**						
	Energy efficiency	**Energy flexibility and storage**	**Comfort**	**Convenience**	**Health, well-being and accessibility**	**Maintenance and fault prediction**	**Information to occupants**
Heating	0.27	0.41	0.16	0.10	0.16	0.32	0.11
Domestic hot water	0.08	0.12	0.00	0.10	0.00	0.10	0.11
Cooling	0.13	0.19	0.16	0.10	0.16	0.15	0.11
Ventilation	0.14	0.00	0.16	0.10	0.16	0.17	0.11
Lighting	0.10	0.00	0.16	0.10	0.16	0.00	0.00
Electricity	0.02	0.03	0.00	0.10	0.00	0.02	0.11
Dynamic building envelope	0.05	0.00	0.16	0.10	0.16	0.05	0.11
Electric vehicle charging	0.00	0.05	0.00	0.10	0.00	0.00	0.11
Monitoring and control	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Sum	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Impact Weightings	0.16667	0.33333	0.08333	0.08333	0.08333	0.16667	0.08333

Table 2 Default SRI weightings for a non-residential building situated in the Western European climate zone.

In the SRI assessment tool, services pertaining to building envelope components are categorized within the domain termed "Dynamic Building Envelope." These services include "Window Solar Shading Control," "Window Open/Closed Control," and "Reporting Performance Information of Dynamic Building Envelope Systems". To discern the impact of alterations in the control strategy of building envelope components on the SRI score, modifications to the functionality levels of the aforementioned services were executed. The resultant variations in the overall SRI score of the building were analyzed.

For building energy simulation, the EnrgyPlus software (version 23.1) was employed in conjunction with its Energy Management System (EMS) feature. EnergyPlus EMS is a flexible and powerful scripting language that allows users to define custom control strategies for building energy models. EMS enables users to implement advanced control logic beyond the standard built-in control options provided by EnergyPlus (15). This research study incorporates the combination of EnergyPlus and Python to simulate buildings equipped with various smart services and smart controlling strategies.

An illustration of the zones, apertures, and the designated points defined for both Daylight Glare Index and lighting calculations is provided in Figure 2. The angles used for calculating the Daylight Glare Index are determined by the furniture layout. Furthermore, Table 3 encompasses the input data that has been taken into account during the modelling process.

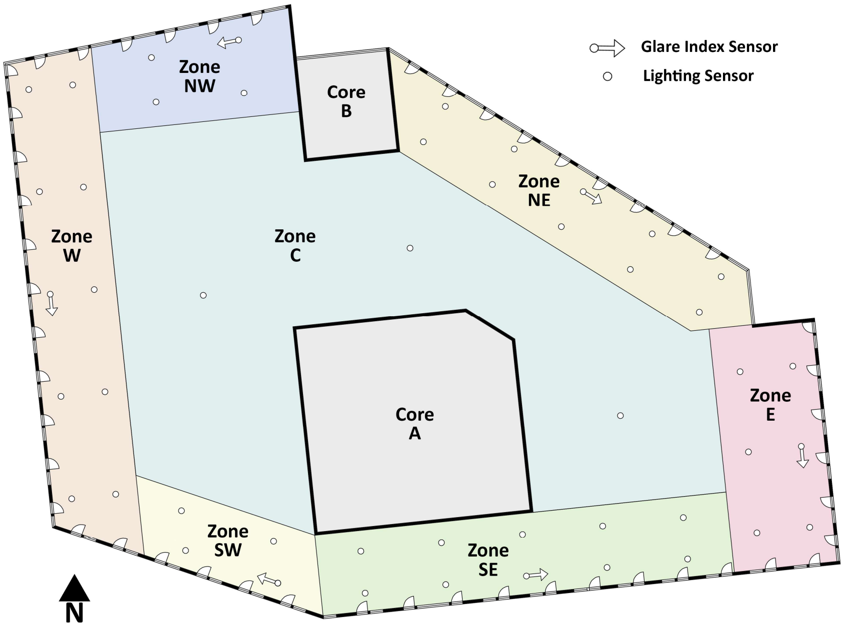


Figure 2 Illustration of EnergyPlus model zoning for a typical floor.

Wall	U-Value	0.25 W/m²K
Window	Glazing U-Value	1.6 W/m²K
	Glazing G-Value	0.27
	Frame U-Value	4.5 W/m²K
	Number of openable windows	49
	Number of fixed windows	54
Shading	Solar and Visible Transmittance	0.1
	Solar and Visible Reflectance	0.8
Indoor Temperature	Winter	20 °C
	Summer	24 °C
Occupied Hours	Weekdays	7:00 to 18:00
Number of People		8 m²/person
Mechanical Ventilation Rate		12 l/s/person
Lighting Level		300 lux
DGI Threshold		22
CO_2 Level Threshold		800 ppm
Outdoor CO_2 Level		420 ppm
Internal Gains	Lights	10 W/m²
	Equipment	18 W/m²

Table 3 Building simulation input data.

4.1 Controlling Scenarios

In the development of control strategies for solar shading and window operations, the primary aim is to ensure that these strategies align with the established functionality levels within the SRI. This alignment enables a comparative evaluation of the effects of different functionality levels on the energy performance of the building.

4.1.1 Controlling Scenarios for Solar Shading

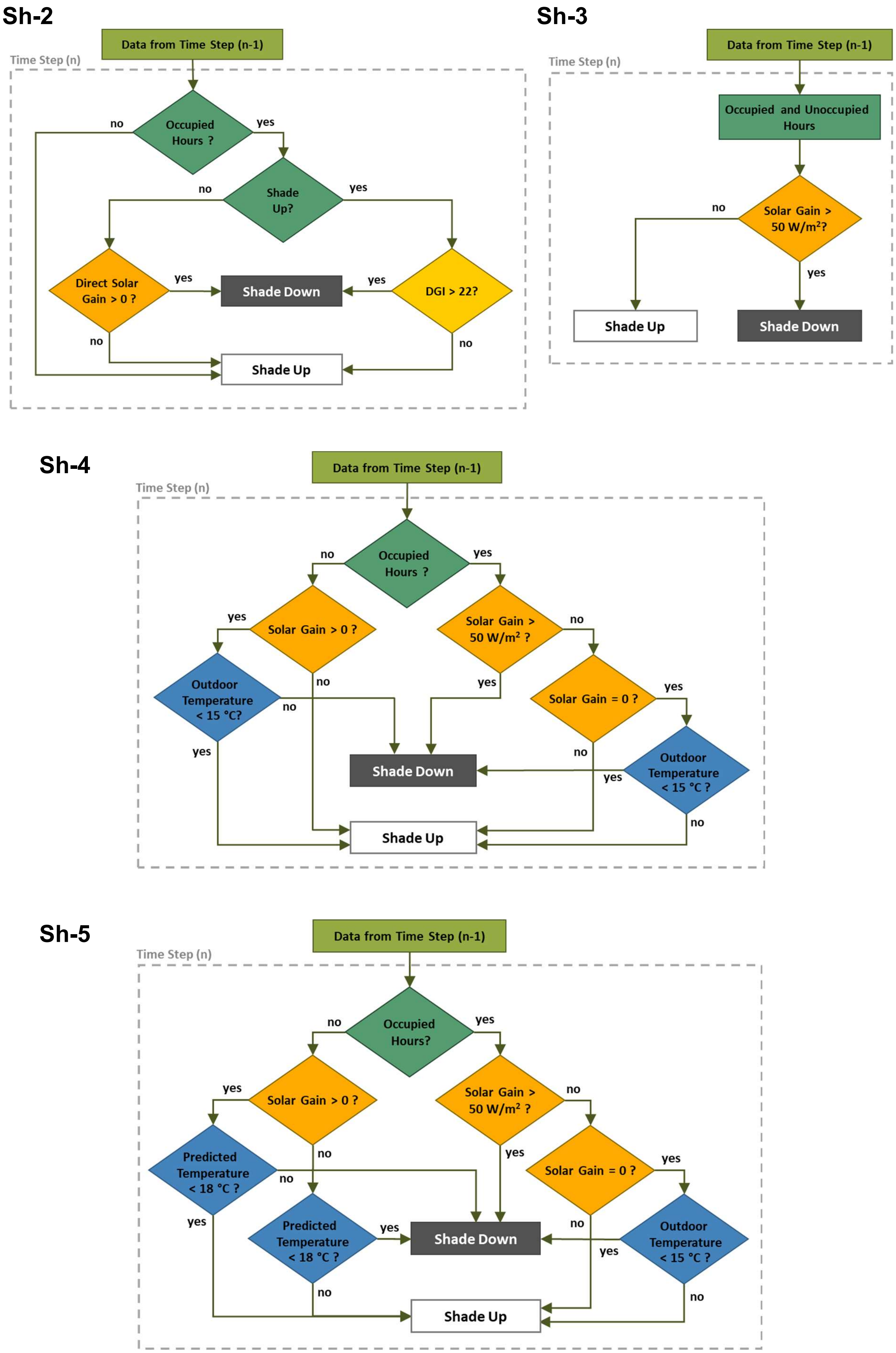
In accordance with the SRI framework, five distinct levels of functionality have been determined for the control of solar shading (Table 4). The controlling scenarios developed for these functionality levels are outlined as follows:

Functionality Level 0: Two scenarios have been considered for this level. In the first scenario (Sh-1), windows have been taken into consideration without the presence of any shading devices. In the second scenario (Sh-2), shading devices are manually controlled by occupants. In this scenario, it has been assumed that occupants close shading devices when the DGI within their workspace exceeds the desired threshold. Also, it is assumed that they open the shadings when there is no direct sunlight on the windows. The shadings are open during unoccupied hours. (Figure 3).

Functionality Level 1: Shading control involves the motorized operation with manual control. At this level, even though it is easier for occupants to change the position of the shading systems, control remains reliant on occupants' behaviour. Consequently, the control scenario for this functionality level has been considered the same as the previous scenario.

Functionality level 2: This level pertains to the motorized operation of shading devices with automatic control based on sensor data. In the developed controlling scenario (Sh-3), the sensor considered is a solar radiation sensor that measures the amount of solar gain on the windows. In this scenario, the shading devices are automatically closed when the solar gain on the windows exceeds 50 W/m^2 (Figure 3). This control strategy has been applied during both occupied and unoccupied times. The determination of this threshold was accomplished through a sensitivity analysis, guaranteeing the maintenance of comfortable lighting conditions for the majority of hours while minimizing energy consumption.

Functionality level 3: This level is a combination of light, blind, and HVAC control. The control algorithm developed for this functionality level incorporates distinct strategies for occupied and unoccupied periods. During occupied periods, similar to the previous scenario, the shades are closed upon the surpassing of solar radiation on the window beyond 50 W/m^2. Furthermore, during instances when solar radiation is absent, and the outdoor temperature falls below a designated threshold (15 °C), the shades are closed to prevent heat loss arising from radiation. The determination of the outdoor temperature threshold is based on a sensitivity analysis. During unoccupied times and weekends, the shades are opened if solar radiation is detected and the outdoor temperature is below 15 °C (Figure 3).


Sh-2

Sh-3

Sh-4

Sh-5

Figure 3 Window shading control algorithms.

Functionality level 4: The highest level of shading control functionality defined is known as predictive control. The control scenario developed for this level closely mirrors the preceding scenario, with the main difference lying in its approach during unoccupied periods. During these intervals, shading conditions are determined based on forecasts of the average outdoor temperature for the upcoming workday's occupied hours. The developed control algorithm utilizes the temperature of the following day from the weather data file as the predicted temperature. In this approach, if solar radiation is detected and the predicted outdoor temperature is projected to be lower than a predetermined threshold (18 °C), the shades will be open to harness solar heat gain. Conversely, if the predicted temperature surpasses this threshold, the shades will be closed to decrease the cooling load during the following occupied hours. In cases where solar radiation is not identified and the anticipated air temperature is lower than the specified value, the shades will be shut to prevent heat loss (Figure 3).

Scenario	Description	SRI Level	Diagram
Sh-1	No shading	0	-
Sh-2	Manual Control	0 - 1	Figure 3 (Sh-2)
Sh-3	Control based on sensor data	2	Figure 3 (Sh-3)
Sh-4	Combined light and HVAC control	3	Figure 3 (Sh-4)
Sh-5	Predictive control	4	Figure 3 (Sh-5)

Table 4 Developed controlling scenarios for window shading.

4.1.2 Controlling Scenarios of Window Operation

In the SRI service pertaining to the control of window operations, four distinct functionality levels have been defined (Table 5). The developed control scenarios for these functional levels are outlined as follows:

Functionality Level 0: This level includes manual window operation or only fixed windows. Two specific scenarios have been developed to correspond with this level. In the first scenario, the windows have been considered fixed, and all ventilation occurs through mechanical systems (Win-1). In the second scenario (Win-2), the windows can be opened by the occupants. In accordance with the building's operational strategy, when the external temperature ranges from 15 to 24 °C, the mechanical ventilation system within the perimeter zones is deactivated. Subsequently, occupants are informed via traffic lights to proceed with window openings. Guided by these conditions, the second scenario of control involves the deactivation of the mechanical ventilation system within perimeter zones, and the opening of windows within the outdoor temperature range of 15 to 24 °C. To prevent discomfort for occupants in indoor spaces, windows will be closed when wind speeds exceed 9 m/s. (Figure 4).

Functionality level 1: This level deals with windows open/closed detection to shut down heating or cooling systems. In the simulation, the ideal load calculation technique was applied to ensure maintenance of the internal temperature within the designated comfort range. Consequently, the option to deactivate the heating and cooling system while a window remains open is rendered unfeasible. In addition, turning off the heating and cooling system has the potential to cause deviations in the internal temperature from the predefined comfort range. This disparity impedes a meaningful comparison between this specific scenario and others wherein the indoor temperature consistently remains within the comfort range. To address this, the designed control strategy for Functionality Level 1 (Win-3) encompasses opening windows only when the heating and cooling systems are off. Based on this scenario, during periods when the outdoor temperature ranges between 17 and 24 °C, the mechanical ventilation within perimeter zones will be deactivated. Furthermore, window openings will be permitted exclusively when the heating and cooling system is inactive (Figure 4).

Functionality Level 2: This level encompasses all the features of the preceding level while introducing the automated operation of windows in response to sensor data. In developing the scenario corresponding to this functionality level (Win-4), alongside the conditions considered for windows operation in the earlier scenario, the opening of windows is restricted to periods when the indoor CO_2 levels exceed 800 ppm (Figure 4).

Functionality Level 3: This level includes all the features of the previous level, along with the centralized coordination of operable windows, such as controlling windows operation to use of free natural cooling. The proposed scenario for this level (Win-5) endeavours to merge the concept of free natural cooling with the conditions established in the earlier stage. Within this scenario, two distinct strategies are considered for occupied and unoccupied periods. During occupied hours, in the case that the heating system is active, the control approach mirrors that of the preceding scenario. However, when the cooling system is active or both heating and cooling systems are inactive, the indoor temperature is compared with the outdoor temperature to harness the benefits of free cooling. If the outdoor temperature is lower than the indoor temperature, the windows are opened to enhance ventilation. However, if the outdoor temperature exceeds the indoor temperature, window opening is restricted to instances where the indoor CO_2 level exceed 800 ppm. During unoccupied periods, when the indoor temperature exceeds 20 °C and the outdoor temperature is lower than the indoor temperature, the windows are opened to exploit the advantages of free cooling (Figure 4). It should be noted in all scenarios related to window operation, all windows associated with each zone operate simultaneously.

Scenario	Description	SRI Level	Diagram
Win-1	Fixed window	0	-
Win-2	Manual control	0	Figure 4 (Win-2)
Win-3	Heating or cooling systems shut down	1	Figure 4 (Win-3)
Win-4	Win-3 + sensor data	2	Figure 4 (Win-4)
Win-5	Win-4 + free cooling	3	Figure 4 (Win-5)

Table 5 Developed controlling scenarios for window operation.

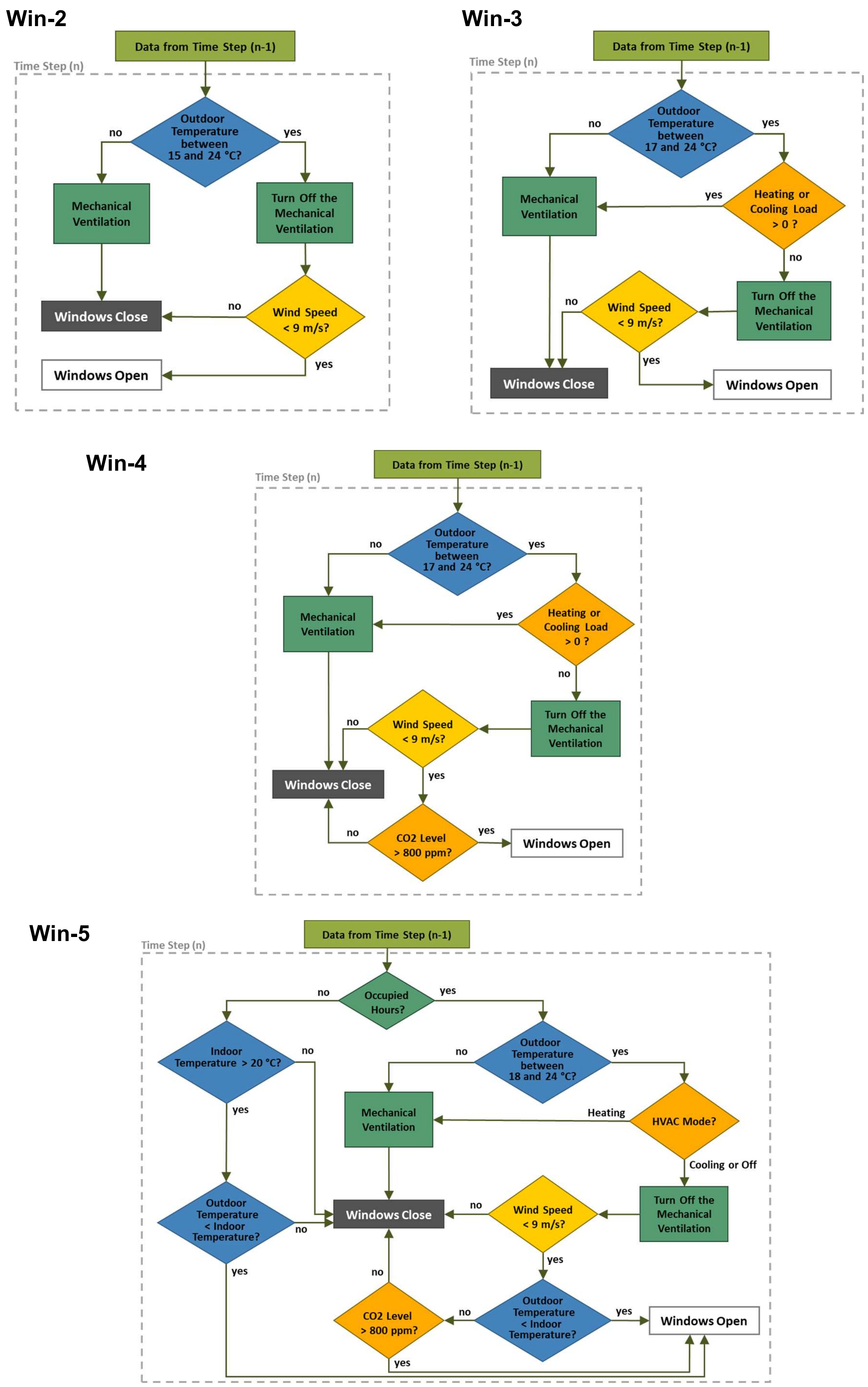


Figure 4 Window opening and closing control algorithms

5.0 Results and Discussion

The case study building underwent an assessment based on the SRI. As illustrated in Figure 5, the building achieved a total SRI score of 43.1%. In general, the installation of a Building Management System (BMS) resulted in high impact scores across all impact criteria, except for the energy flexibility and storage criterion. The low score in this particular criterion can be attributed to the lack of communication between the grid and the building's control systems. Furthermore, it is important to note that the energy flexibility and storage criterion carries a weight of 33% in the overall building score. Consequently, despite obtaining high scores in other impact criteria, the building's total score remains relatively low.

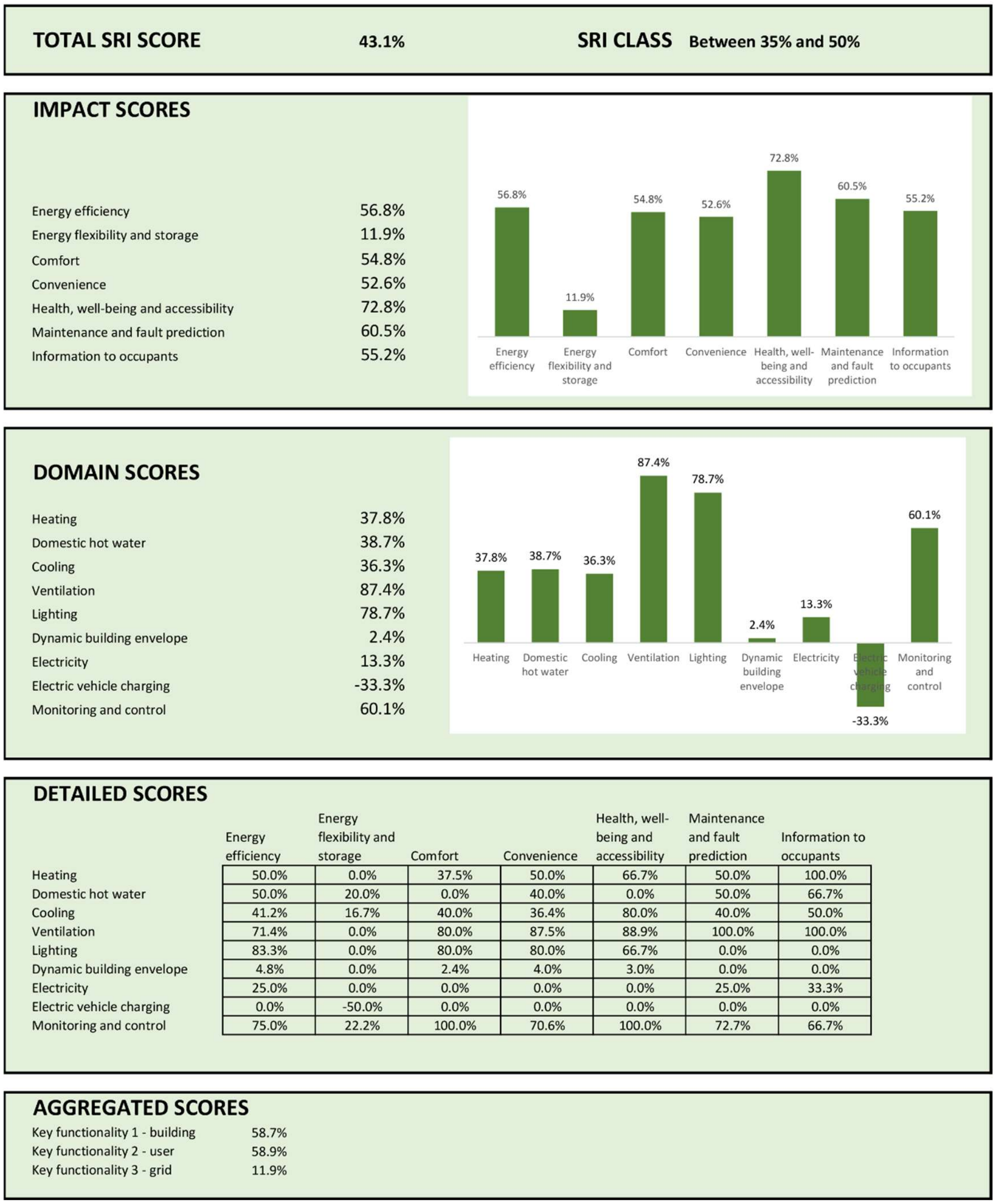
Given that the primary aim of this study is to investigate how changes in services related to the dynamic envelope impact both the building's SRI score and its overall performance, an in-depth analysis of the implications of adjustments to the functionality levels of services within this domain was conducted. It's important to note that in the SRI scheme certain services may be deemed not applicable to a particular building. In such instances, its score is not considered in the calculation of the maximum obtainable score. The impact of these specific conditions on the building's SRI score, as well as the effects of modifications in the functionality levels of services related to the dynamic envelope domain, was examined in more detail.

As indicated in Table 1, when the functionality level of the service related to window solar shading control is elevated from level 0 to level 4, the overall SRI score of the building increases from 43 to 45%. However, if "not applicable" is selected for this service, the building's score reaches 44.4%, which is in close proximity to functionality level 3. Therefore, not using movable shading in the building can result in a higher SRI score compared to when the building is equipped with movable shading controlled at functionality levels between levels 0 and 2.

Regarding the service related to window opening and closing control, it is crucial to emphasize that, unlike the previous service, it has an influence on the total attainable score even when considered as not applicable to the building. Consequently, selecting the "not applicable" option results in the building's total score remaining at 43%, which is identical to the situation when the functionality level of the service is set at level 0. However, when the functionality level for window operation control is elevated from level 0 to level 3, the total score of the building increases from 43% to 44.1%.

When evaluating the service related to reporting information regarding the performance of dynamic building envelope systems, like the shading control service, it can be categorized as "not applicable." In such a case, the overall SRI score of the building will be approximately the same as the situation where the building is equipped with a reporting system set at functionality level 3. The highest achievable score for the building, assuming it has a level 4 functionality for this service, would be 44.1%.

In total, the collective impact of the services related to the building dynamic envelope domain on the overall SRI score of the case study building amounts to 4.1%. In other words, if the building has a functionality level of 0 for all three services pertaining to this domain, its score will be 43%. However, if it achieves the highest functionality level in these services, the total score of the building will increase to 47.1%.



TOTAL SRI SCORE 43.1% **SRI CLASS** Between 35% and 50%

IMPACT SCORES

Energy efficiency	56.8%
Energy flexibility and storage	11.9%
Comfort	54.8%
Convenience	52.6%
Health, well-being and accessibility	72.8%
Maintenance and fault prediction	60.5%
Information to occupants	55.2%

DOMAIN SCORES

Heating	37.8%
Domestic hot water	38.7%
Cooling	36.3%
Ventilation	87.4%
Lighting	78.7%
Dynamic building envelope	2.4%
Electricity	13.3%
Electric vehicle charging	-33.3%
Monitoring and control	60.1%

DETAILED SCORES

	Energy efficiency	Energy flexibility and storage	Comfort	Convenience	Health, well-being and accessibility	Maintenance and fault prediction	Information to occupants
Heating	50.0%	0.0%	37.5%	50.0%	66.7%	50.0%	100.0%
Domestic hot water	50.0%	20.0%	0.0%	40.0%	0.0%	50.0%	66.7%
Cooling	41.2%	16.7%	40.0%	36.4%	80.0%	40.0%	50.0%
Ventilation	71.4%	0.0%	80.0%	87.5%	88.9%	100.0%	100.0%
Lighting	83.3%	0.0%	80.0%	80.0%	66.7%	0.0%	0.0%
Dynamic building envelope	4.8%	0.0%	2.4%	4.0%	3.0%	0.0%	0.0%
Electricity	25.0%	0.0%	0.0%	0.0%	0.0%	25.0%	33.3%
Electric vehicle charging	0.0%	-50.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Monitoring and control	75.0%	22.2%	100.0%	70.6%	100.0%	72.7%	66.7%

AGGREGATED SCORES

Key functionality 1 - building	58.7%
Key functionality 2 - user	58.9%
Key functionality 3 - grid	11.9%

Figure 5 Case study building's SRI assessment result.

Generally, the primary aim of developing building assessment systems, such as the existing building energy assessment systems or the green building rating systems, is to facilitate the comparison of the performance of different buildings. However, as noted in previous studies , the triage method employed in the SRI system has rendered it challenging to compare buildings based on their scores. This challenge arises from the fact that the calculation of each building's score is based on its unique maximum obtainable score. As a consequence, the variations in the maximum attainable scores of different buildings make it impractical to compare their overall SRI scores.

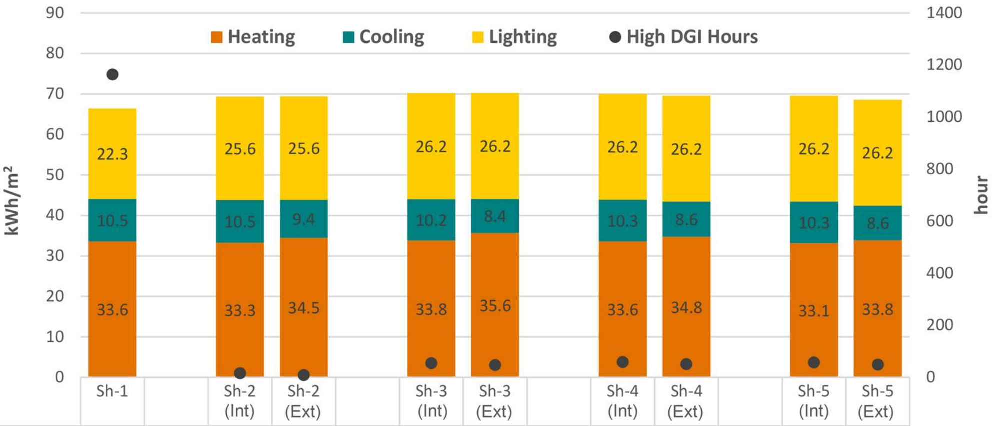
Functionality Level		Dynamic Envelope score	Total SRI score
Window solar shading control			
Not Applicable		0	44.4
Level 0	No sun shading or only manual operation	0	43
Level 1	Motorized operation with manual control	9.6	43.4
Level 2	Motorized operation with automatic control based on sensor data	19.8	43.9
Level 3	Combined light/blind/HVAC control	32.5	44.5
Level 4	Predictive blind control (e.g. based on weather forecast)	38.1	45
Window open/closed control			
Not Applicable		0	43
Level 0	Manual operation or only fixed windows	0	43
Level 1	Open/closed detection to shut down heating or cooling systems	14.6	43.5
Level 2	Level 1 + Automised mechanical window opening based on room sensor data	20.2	44
Level 3	Level 2 + Centralized coordination of operable windows, e.g. to control free natural night cooling	22.3	44.1
Reporting information regarding performance of dynamic building envelope systems			
Not Applicable		0	43.7
Level 0	Position of each product & fault detection	0	43
Level 1	Position of each product, fault detection & predictive maintenance	16.7	43.4
Level 2	Position of each product, fault detection, predictive maintenance, real-time sensor data	20.8	43.6
Level 3	Position of each product, fault detection, predictive maintenance, real-time & historical sensor data	25	43.8
Level 4	Position of each product & fault detection	39.6	44.1

Table 6 Case study building's SRI score with different functionality levels in services related to the dynamic envelope.

To assess the impact of changes in the functionality levels of services related to the dynamic envelope domain on building performance, a building energy simulation was conducted using the developed control scenarios. The performance metrics taken into consideration encompass heating and cooling demands, lighting load, and the duration of hours when the DGI exceeds the comfort threshold. In the results, the average value of hours for six glare sensors positioned within six perimeter zones is taken into account.

In Figure 14, the results for all the developed shading control scenarios for both internal and external shades are presented. It is evident from the results that the variations in the building's energy consumption among scenarios from the second to the fifth, which maintain relatively similar lighting comfort conditions, are not substantial. In the automated controlling scenarios, for internal shading, the energy consumption reduction in the fourth and fifth scenarios compared to the third scenario is only approximately 0.2% and 0.9%, respectively. In the case of external shading, these reductions are 1% and 2.4%, respectively. Furthermore, the SRI score of the building has increased by 0.6% and 1.1% in the fourth and fifth scenarios, respectively, when compared to the third scenario.

Concerning the second scenario, which involves manual control, it is noteworthy that the energy consumption is lower than in the automatic control scenarios. This can be attributed to the assumption made about occupant behaviour in controlling the shading devices. The assumption is that occupants close shading devices when the DGI within their workspace exceeds the desired threshold, and they open the shadings when there is no direct sunlight on the windows. However, in reality, occupants' behaviour includes variations and errors that can potentially increase the building's energy consumption.



	Sh-1	Sh-2	Sh-3	Sh-4	Sh-5
Dynamic Envelope Domain Score	0	0 - 9.6	19.8	32.5	38.1
Building SRI Total Score	43	43 - 43.4	43.9	44.5	45

Figure 6 The simulation results and SRI score of the building in different shading control scenarios with internal (Int) and external (Ext) shadings.

The limited impact of changes in shading control conditions on heating and cooling loads can be attributed to the passive design strategies incorporated into the case study building. The building's design includes features such as reduced glazing area on sun-facing facades and a relatively low window G-value of 0.27, which minimises the entry of solar radiation into the indoor environment.

To evaluate the impact of window characteristics on the efficacy of solar shading strategies, simulations were conducted specifically for windows with higher G-values. Two window types with elevated G-values were included in the simulations (Table 7). Figure 7 displays the outcomes from these simulations alongside those for the current building (Glaz1). It is evident that in scenarios employing manual shading control strategies, the energy consumption across buildings with different window types is quite similar. However, when employing shading controls with higher functionality levels, the reduction in building energy consumption is more pronounced for windows with higher G-values. For instance, in Glaz1, the building's energy consumption in the Sh-5 scenario of internal shading is nearly identical to that in the manual control scenario (Sh-2). In contrast, the comparison between these scenarios in Glaz2 shows a 1.3% decrease in energy consumption, and for Glaz3, this reduction increases to 2.9%. Moreover, employing external shading amplifies this energy consumption reduction at higher functionality levels. For Glaz2 and Glaz3 with external shading, the energy consumption in the Sh-5 scenario is 3.1% and 4.2% lower than in the Sh-2 scenario, respectively.

As demonstrated, the specifications of windows and the placement of shading can significantly impact the performance of solar shading devices. In certain cases, these design strategies can render high-level shading control strategies ineffective. However, according to the SRI assessment methodology, the building can achieve a higher score solely by equipping the shading device with high-functionality level control, regardless of its actual impact on energy performance. Hence, it is crucial to concurrently consider building envelope design, window shading design, and their control strategy alongside the building's SRI score to attain the optimal outcome in building performance.

Window Glazing Type	U-Value	SHGC	T_{vis}
Glaz1 (Current Building)	1.6	0.27	0.46
Glaz2	1.6	0.53	0.78
Glaz3	1.6	0.70	0.76

Table 7 Specifications for window glazing utilised in assessing the impact of the glazing G-value on the effectiveness of various shading control strategies.

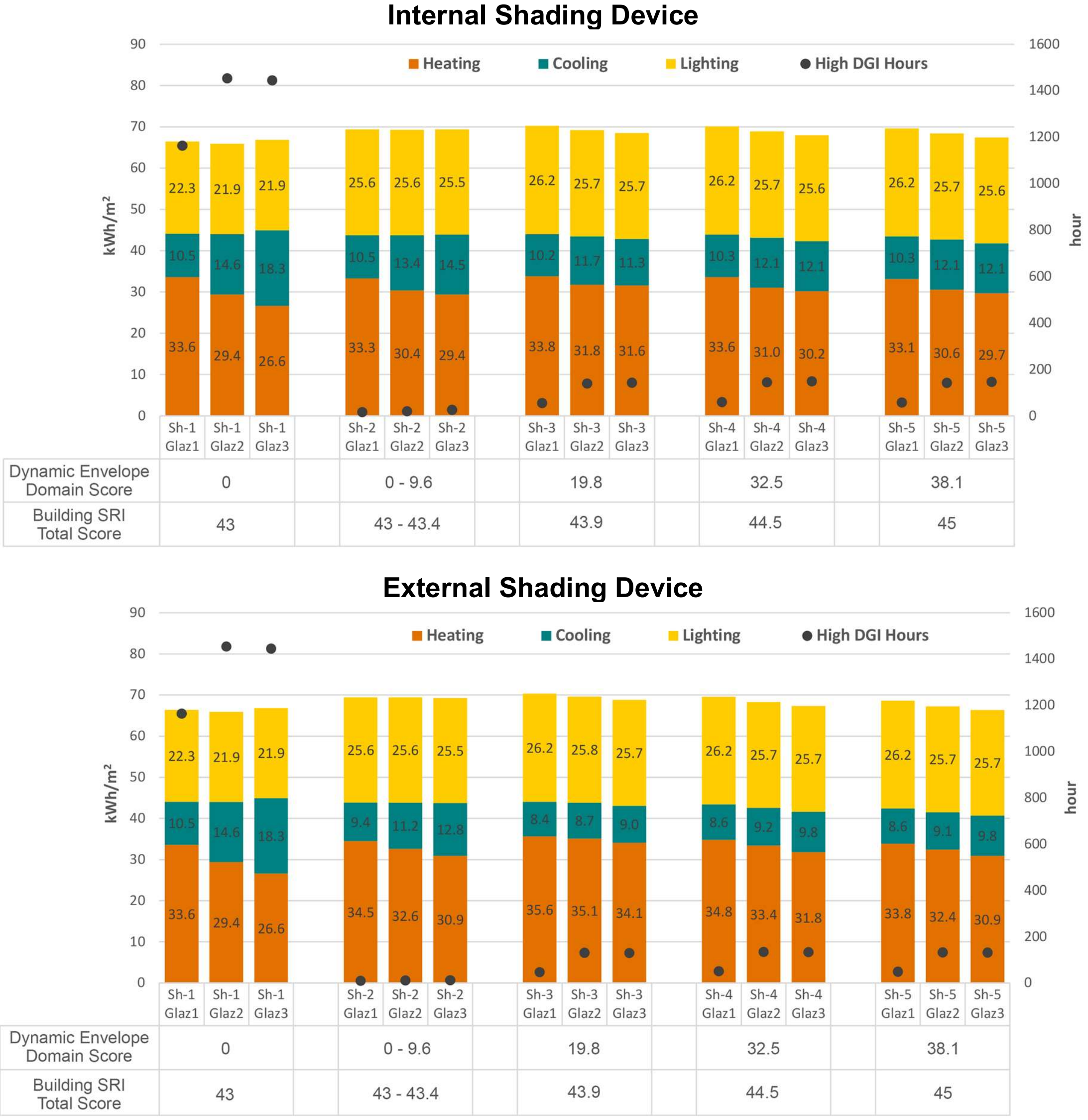


Figure 7 The simulation results and SRI score of the building with different window glazing in different shading control scenarios with internal and external shadings.

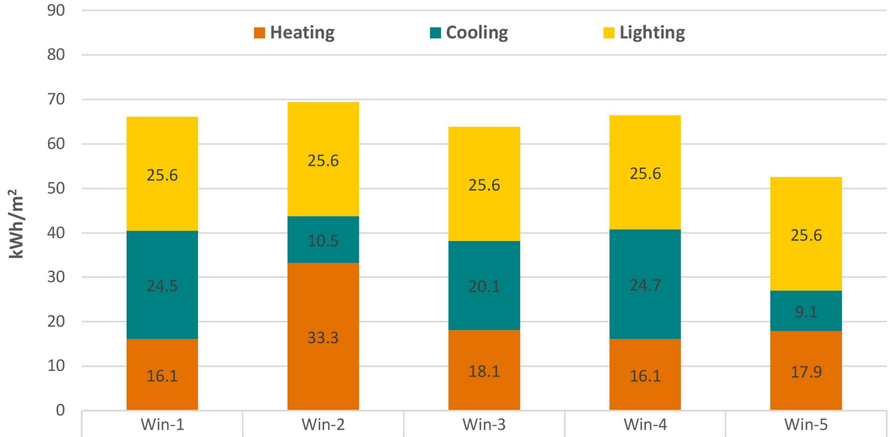
Figure 8 displays the results of the energy performance of the building for various scenarios of window opening and closing control. In the first scenario, which involves fixed windows, the consistent and limited mechanical air change rate results in a low heating load but a notably high cooling load. In the second scenario, where windows are controlled manually, there has been a significant reduction in cooling load compared to the fixed window scenario. This reduction is related to an increase in the air change rate and the utilisation of free cooling. However, this increased air exchange rate has caused a notable rise in heating load. Consequently, the total energy demand in the second scenario surpasses that of the first scenario. It's worth noting that the results do not account for the electricity consumption of the fans in the mechanical ventilation system. This factor could have an impact on the overall building energy consumption.

In the third scenario, where window operation is automatically controlled and limited to times when the heating and cooling systems are not active, energy demand decreases by approximately 8% compared to manual control. This reduction is accompanied by an increase in cooling load and a decrease in heating load.

In the fourth scenario, where window opening is restricted to conditions where indoor CO_2 levels exceed acceptable levels, the total energy demand is more than in the third scenario, despite a 1.5% higher SRI score. In this scenario, the reduction in window opening time leads to a decreased heating load, but it also results in an increased cooling load due to reduced utilization of free cooling.

The approach in the fifth scenario is to maximise the utilisation of free cooling. As evident from the results, the cooling load in this scenario is lower compared to other scenarios. The total energy demand in this scenario is 24.2% less than in the manual control scenario and approximately 17.6% less than in the third scenario. Despite the substantial impact of the window opening and closing control strategy on the building's energy performance, the shift in the building's total SRI score from the lowest functionality level of this service to the highest functionality level is only 1.1%.

Overall, the results obtained suggest a lack of significant correlation between the scores of the SRI dynamic envelope and the building's energy performance. The variation in the building's energy performance can be notably more pronounced than the alteration in the SRI score, or the adjustment in the SRI score may not necessarily induce a change in the building's energy performance. Therefore, it's advisable to consider the building's energy performance alongside the SRI score, as well as the interaction between smart services and building design, to achieve maximum efficiency.



	Win-1	Win-2	Win-3	Win-4	Win-5
Dynamic Envelope Domain Score	0	0	14.6	20.2	22.3
Building SRI Total Score	43	43	43.5	44	44.1

Figure 8 The simulation results and SRI score of the building in different window opening-closing control scenarios.

6.0 Conclusion

In this study, the relationship between the Smart Readiness Indicator (SRI) score of a building and its performance was assessed, focusing on the smart services associated with the dynamic building envelope. An office building situated in London was chosen as the case study and underwent an extensive assessment using the SRI. Furthermore, its performance was assessed using dynamic energy simulations, considering various control strategies for movable shading devices and window operations. The performance metrics considered encompass heating and cooling demands, lighting load, and the duration of hours when the DGI exceeds the comfort threshold. It is important to note that auxiliary energy consumption is not considered in this study. From the findings obtained, the following conclusions can be drawn:

- In the SRI methodology, employing a triage process that holds the potential to exclude particular domains and services during the assessment procedure can modify the highest achievable score. Consequently, this alteration impacts the building's final SRI score. Hence, the assessment approach in the SRI calculation process can significantly influence the ultimate SRI score of the building.
- Simply adding smart services with high functionality levels to a building doesn't guarantee improved performance. The building's design must be carefully aligned with these systems and their control strategies to achieve optimal performance. For instance, to attain optimal performance, it is crucial to consider factors such as the shading control strategy and the size and properties of windows (e.g., U-Value and SHGC) simultaneously.
- A high SRI score does not guarantee high building performance, and conversely, a low SRI score doesn't necessarily indicate poor building performance. Hence, it is advisable to simultaneously consider both a building's SRI score and its actual performance. It should also be noted that energy performance was used as a proxy for building performance in this study. The evaluation of a building’s environmental performance should be extended to other environmental parameters such as thermal comfort and indoor air quality.
- Additional research is required in exploring the interplay between architectural design and control systems, such as investigating the impact of factors like window opening size and window-to-wall ratio on the effectiveness of control strategies associated with dynamic envelope.

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Acknowledgements

This research was made possible by support from the EPSRC Centre for Doctoral Training in Energy Resilience and the Built Environment , grant number EP/S021671/1, and with financial support from [EPSRC + UCL ISAD + AHMM].