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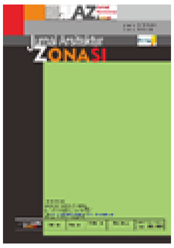

Analysis of the Adaptive Secondary Skin at the Quadracci Pavilion, Milwaukee Art Museum: Function, Aesthetics, and Smart Technology

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A B S T R A C T

Driven by increasing climate volatility, the concept of smart architecture is innovating building envelope design. Adaptive façades with secondary skins represent a critical advancement, actively enhancing energy efficiency, controlling the microclimate, and providing dynamic aesthetic expression. By modulating solar heat gain and optimizing daylight, these systems reduce reliance on artificial HVAC and lighting. This study analyzes a pioneering example: the adaptive secondary skin of Santiago Calatrava's Quadracci Pavilion at the Milwaukee Art Museum. The research focuses on its iconic Burke Brise Soleil—a kinetic, wing-like structure that opens and closes—to evaluate its functional, aesthetic, and technological impact. A qualitative-descriptive approach was employed, integrating a literature review with visual architectural analysis grounded in frameworks of climate-responsive design and smart building principles. The findings reveal the Pavilion's secondary skin significantly enhances thermal comfort by filtering solar radiation while maximizing natural lighting. Furthermore, its celebrated kinetic movement strengthens the building's visual identity and transforms it into a dynamic landmark. This research concludes that technology-integrated adaptive secondary skins offer a powerful model for sustainable architectural solutions, demonstrating a paradigm shift from static envelopes to responsive, intelligent systems that merge engineering and artistry.

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1. INTRODUCTION

Modern architecture is continuously evolving in response to the dynamics of the times. Today, buildings are demanded not only to provide shelter but also to respond to environmental changes, be energy-efficient, and remain visually appealing. Global challenges such as climate change, limited natural resources, and rapid urban growth compel architects to present smarter and more sustainable design solutions. It is in this context that the concept of smart architecture has begun to develop and gain widespread attention. This concept emphasizes the integration of technology, energy efficiency, user comfort, and environmental sustainability within a single building entity (Aldhaher & Selçuk, 2024).

One element now frequently used in smart architecture is the secondary skin, an additional layer on the building's facade. Its function is not only to protect against heat and sunlight but also to serve as a system that helps regulate natural lighting, air circulation, and adapt to the local climate. The application of this system is also part of climate-responsive architecture, which focuses on creating a comfortable thermal environment through passive design approaches (Saifudeen & Mani, 2024). Recent research highlights that secondary skins have significant potential to improve thermal efficiency and visual comfort, especially in challenging tropical climates (Qahtan, 2019). Beyond these functional benefits, secondary skins also possess high aesthetic value. This allows for the exploration of forms, patterns, and materials that make the building facade more expressive and contextually appropriate (Ezz et al., 2024.

Recent studies have explored various aspects of secondary skins. For instance, a study by Li et al. (2024) showed that using porous and perforated materials on a secondary skin can reduce indoor temperatures by up to 4°C during the day in tropical regions. The application of a secondary skin is an effective passive cooling strategy (Umar, 2023). The use of a Double-Skin Facade (DSF) can significantly enhance thermal and lighting comfort in tropical countries (Wicaksono & Purwanto, 2022), as well as reduce average energy consumption by 28% across various climates (Pomponi et al., 2016). Meanwhile, Husarikova et al. (2025) investigated the influence of double facades on natural lighting intensity and found that an adaptive design could reduce glare discomfort by 40-60%. Furthermore, a recent study by Young et al. (2025) involving Phase Change Materials (PCM) in passive building envelopes has the potential to reduce total energy consumption by up to 48%, life cycle costs by 30%, and CO2 emissions by 53%. Another study by Z. Li et al. (2025) discusses the integration of automated sensors and real-time shading technology, enabling the secondary skin to meet visual quality and shading targets directly and dynamically. In a more technological study, Ghoneim (2025) demonstrated that facades with adaptive systems can improve performance, resulting in significant energy savings of up to 40% in high-rise buildings. However, most research still focuses separately on a single aspect—be it thermal performance, aesthetics, or technology—without examining the integration of all three

A holistic study that unifies adaptive functions, architectural visual value, and the use of smart technology in secondary skin systems is still very limited, especially in the context of urban tropical regions like Indonesia. In response to this gap, this research selects the Quadracci Pavilion at the Milwaukee Art Museum as a representative case study to evaluate the integration of function, aesthetics, and smart technology in a secondary skin system. This building serves as a tangible example of an adaptive facade system that not only functions technically but also reflects an iconic architectural expression through the integration of kinetic structures and innovative design.

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The Quadracci Pavilion, designed by Santiago Calatrava with a structure capable of opening and closing like wings, demonstrates how technology can be a medium for architecture that is both adaptive and expressive (Akgün et al., 2022). The secondary skin element in the form of the Burke Brise Soleil on this pavilion responds to surrounding lighting and climate conditions. In addition to energy efficiency, the presence of this dynamic facade also imparts a strong visual character, making the building a contemporary architectural icon.

Given this situation, this research is important to conduct. Moreover, in tropical and densely populated urban areas, such as many cities in Indonesia, the need for buildings that are adaptive to the climate and environment is increasingly urgent. By studying how the Quadracci Pavilion effectively applies an adaptive secondary skin, this research also aims to open up possibilities for applying similar strategies in the local Indonesian context. The secondary skin has the potential to be a solution that is not only energy-efficient but also enriches the architectural expression of buildings. Therefore, this study aims to explore in greater depth how secondary skins can be maximized in terms of function, such as microclimate control; aesthetics, as a shaper of architectural identity; and technological integration, such as responsive materials and automation systems. Thus, it is hoped that this research can support the creation of buildings that are truly smart, comfortable, and sustainable in the future.

2. RESEARCH METHOD

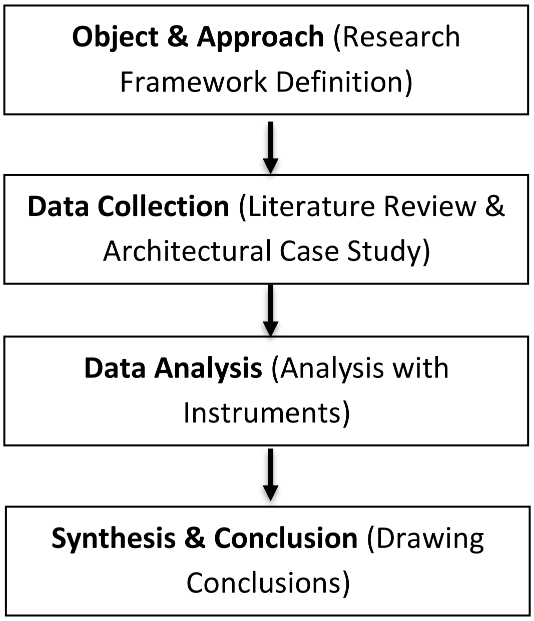

Table 1. Research Methodology

This research employs a qualitative-descriptive approach to deeply understand the role of adaptive secondary skins in smart architecture through the aspects of function, aesthetics, and smart technology. The main object of this study is the Quadracci Pavilion at the Milwaukee Art Museum, which is analyzed as a representative case study of the application of adaptive secondary skin in a contemporary design context.

The method used includes a literature review and an architectural case study. The literature review covers scientific sources such as journals, books, articles, and official reports that discuss the concepts of smart architecture (Kolarevic & Parlac, 2020), adaptive facade

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design (Carlucci et al., 2024; Fathullah et al., 2021), energy efficiency (Jafari et al., 2021; GhaffarianHoseini et al., 2020), and aesthetics in contemporary architecture (Cheng et al., 2019; Ciftcioglu & Yildiz, 2021). The literature focus is directed at theories of climate-responsive design (Lathifah et al., 2021) and smart facade technology (Sanei & Memari, 2019).

The case study focuses on the architectural analysis of the Quadracci Pavilion, particularly the Burke Brise Soleil element as a representation of an adaptive secondary skin. Visual and technical data were examined through project documentation, architectural publications, and credible online sources. The analysis instrument includes an architectural observation form, which consists of indicators for climatic function (lighting, ventilation, and thermal protection) as developed in the studies of GhaffarianHoseini et al. (2020) and Nourian et al. (2023), aesthetic quality (form, pattern, visual expression) as discussed by Ciftcioglu and Yildiz (2021), and technology integration (kinetic mechanisms, automation, and innovative materials) based on models from Heidari Matin et al. (2023), Rahmani and GhaffarianHoseini (2022), and Wu et al. (2022). With this approach, the analysis is conducted systematically on the adaptive function of the facade, the aesthetic value of its dynamic form, and the relevance of smart facade technology that can respond to climate changes in real time.

3. RESULTS AND DISCUSSION

3.1 Discussion Content

The Quadracci Pavilion is an iconic part of the Milwaukee Art Museum designed by the visionary architect Santiago Calatrava. This building is not merely a transitional space to the gallery areas but has become a symbol of the integration of art, structure, and technology in modern architecture. Made of steel and glass, the Pavilion is built on a sturdy concrete structure south of the gallery area and stands majestically with 17 specially designed A-frames. These frames vary in size, from about 8 meters to 30 meters, and are designed to support the main component of the adaptive facade structure, the Burke Brise Soleil.

The Burke Brise Soleil is a state-of-the-art interpretation of the adaptive secondary skin concept, functioning responsively to environmental conditions. This structure resembles two giant wings composed of 72 steel blades, which can open and close automatically according to the intensity of sunlight and wind speed. When the system detects strong winds exceeding 37 km/h for more than three seconds, the blades close automatically to avoid excessive structural stress (Witzling, 2016). This automated system demonstrates how smart technology can be utilized to enhance safety, energy efficiency, and thermal comfort without sacrificing aesthetic value.

Image 1. Quadracci Paviliun Building
(Source: Pinterest, 2017)

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The Pavilion is described as a "giant oval table" with a large opening in the center leading to a glass atrium. This structure is supported by four large legs consisting of two sets of vertical columns on the east and west sides, which are firmly embedded in the foundation walls. The Pavilion also serves as the base for a cable-stayed pedestrian bridge and a rear support beam that are harmoniously integrated into its architectural structure.

To accommodate such structural complexity, the Pavilion was modeled using finite element analysis simulations to predict structural behaviors such as deflection and cracking. A post-tensioning system was also added to the upper part to increase tensile strength and maintain stability. The building's spine, a 635 mm diameter steel pipe, acts as the main supporting axis where the A-frames rest and connect precisely, creating a geometric form that is not only structurally efficient but also visually captivating.

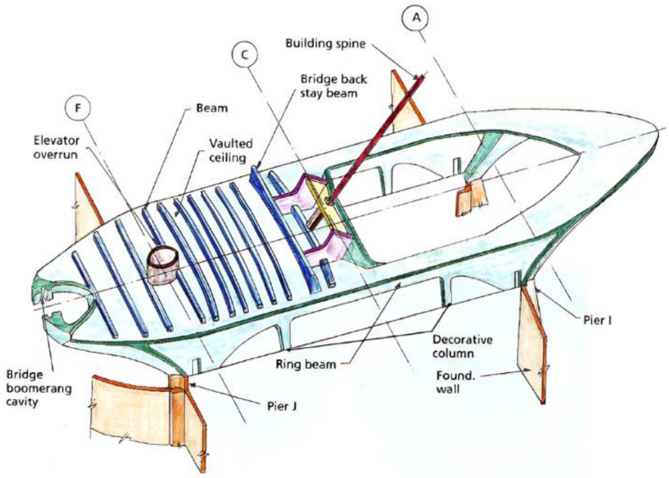

Image 2. Quadracci Pavilion Artial Frame
(Source: Ebook Milwaukee Art Museum, 2015)

The glass atrium frame, perched atop the pavilion, is designed with a 48.36-degree inclination angle, parallel to the cable-supported bridge pylon. This harmonious relationship between the structural system, architectural form, and responsive technology is tangible proof that an adaptive secondary skin is not just an additional element but a primary design strategy in creating a building that is smart, aesthetic, and contextual.

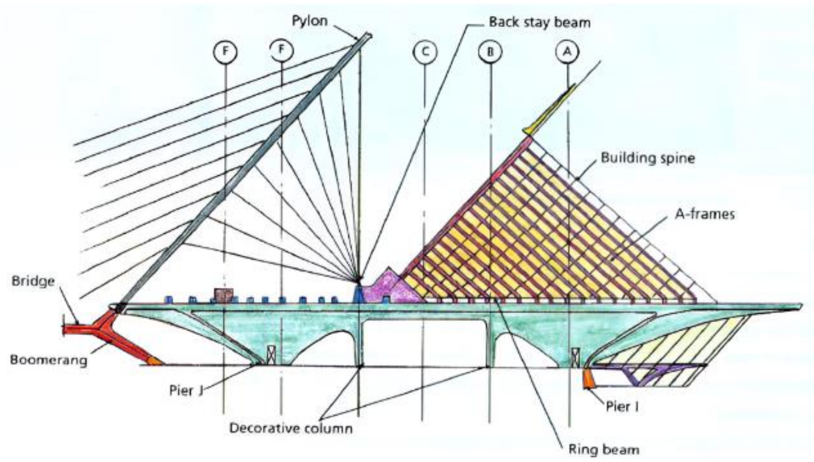

Image 3. Quadracci Pavilion Frame
(Source: Ebook Milwaukee Art Museum, 2015)

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With this approach, the Quadracci Pavilion proves that architecture is not only about form and function but also about how a building can actively respond to its environment and provide a dynamic spatial experience for its users. The Pavilion also serves as an ideal example of the application of smart architecture that integrates design innovation, energy efficiency, and artistic expression in a unified manner.

1) Thermal Perfomance and Environmental Adaptation

The Burke Brise-Soleil is one of the most distinctive and iconic elements of Santiago Calatrava's design for the Quadracci Pavilion at the Milwaukee Art Museum. This structure is located above the main atrium made of glass and steel, known as Windhover Hall.

Image 4. Windhover Hall
(Source: Website Milwaukee Independent, 2022)

The Brise-Soleil takes the form of two giant wings that spread over the building, creating an impression that is both grand and functional. Each wing consists of 36 rectangular tube-shaped steel blades, each with a fixed width of 330 mm, but with varying lengths, depths, and thicknesses. These blades are securely connected by steel spacers and are entirely supported by a rotating "spine".

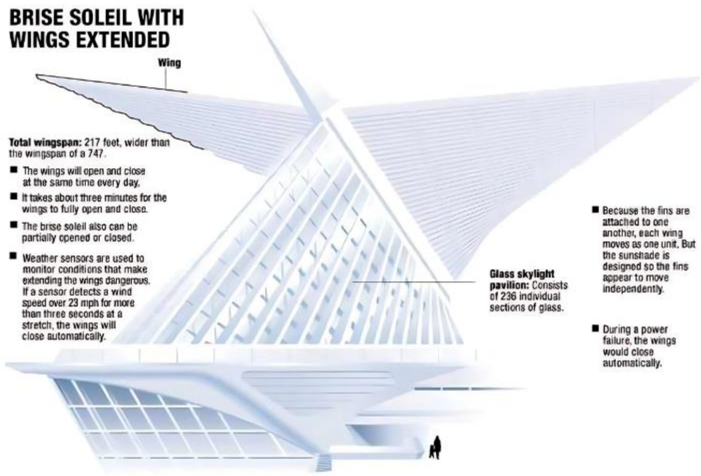

Image 5. Quadracci Paviliun Building
(Source: Ebook Milwaukee Art Museum, 2015)

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The drive system of the Brise-Soleil uses 11 pairs of hydraulic actuators, allowing the blades to open and close up to 90 degrees. This movement not only creates a stunning visual display but also serves a crucial function in regulating lighting and temperature inside the building. When the wings are open, sunlight can optimally enter Windhover Hall, reducing the need for artificial lighting. Conversely, when the sunlight is too intense or during extreme weather like strong winds, the system automatically closes to protect the interior of the building from excessive heat radiation and wind pressure. The presence of this adaptive facade system plays a vital role in maintaining thermal comfort indoors. With its ability to adjust to weather changes in real-time, the Brise-Soleil helps reduce the workload of the air conditioning system. This has a direct impact on the overall energy efficiency of the building. Recent research also shows the effectiveness of this strategy: adaptive facade systems like this can reduce energy consumption by up to 30% in hot climates (Z. Li et al., 2025).

In addition to its functional benefits, this structure also offers high aesthetic value. The movement of the wings opening and closing resembles a bird flapping its wings, creating a dramatic and dynamic visual experience for visitors. This demonstrates how adaptive secondary skin elements not only contribute to creating a more environmentally friendly building but also strengthen its visual identity and overall architectural appeal. In other words, the Burke Brise Soleil is a tangible example of how technology and design can harmoniously combine to create architecture that is smart, efficient, and full of meaning.

2) Aesthetics

Besides providing technical and functional benefits, the adaptive secondary skin on the Quadracci Pavilion also possesses a very strong aesthetic value and symbolic meaning. The form of the giant, movable wings was designed not only to regulate light and temperature inside the building but also to create a powerful and moving visual impression. These wings resemble a seagull in flight or the sails of a ship billowing, a form deliberately chosen to reflect the building's proximity to Lake Michigan and to elevate the local cultural identity of Milwaukee, a city with a rich maritime history. The opening and closing motion of the wings not only creates a dynamic appearance but also strengthens the building's presence in the city's landscape, making it an easily recognizable and meaningful architectural icon and city landmark (Ezz et al., 2024).

From an aesthetic viewpoint, the structure is captivating. The "breathing" motion of the wings each day presents a living visual experience for anyone who sees it—whether from a distance or from within the building. Visitors arriving when the wings are open will experience a spacious, bright, and nature-integrated atmosphere, while when closed, the space becomes more shaded and serene. This effect creates an emotional spatial experience, where architecture becomes not just a place but also creates a certain mood and feeling.

Moreover, this design approach also adopts the principle of biomimetics, which is to imitate forms and functions from nature. For example, the wing's movement and structure, similar to a bird's flapping, or the blades resembling leaf structures, not only beautify the appearance but also help control light and heat passively. In this way, the building becomes more energy-efficient while also providing better visual comfort by maintaining natural light levels without creating excessive glare (GhaffarianHoseini et al., 2020). The presence of this element makes the building not just a place for activities, but also a medium of architectural expression capable of telling a story, building an identity,

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and creating a connection between humans, nature, and technology. This is a real manifestation of how an adaptive secondary skin is not just about efficiency, but also about meaningful aesthetics and architecture that speaks.

3) Integration of Sensor and Automation Technology

The Quadracci Pavilion at the Milwaukee Art Museum is a contemporary architectural icon that represents a comprehensive integration of kinetic architecture, adaptive technology, and the principles of smart architecture. Designed by Santiago Calatrava, the building showcases a futuristic, functional, and aesthetic design approach.

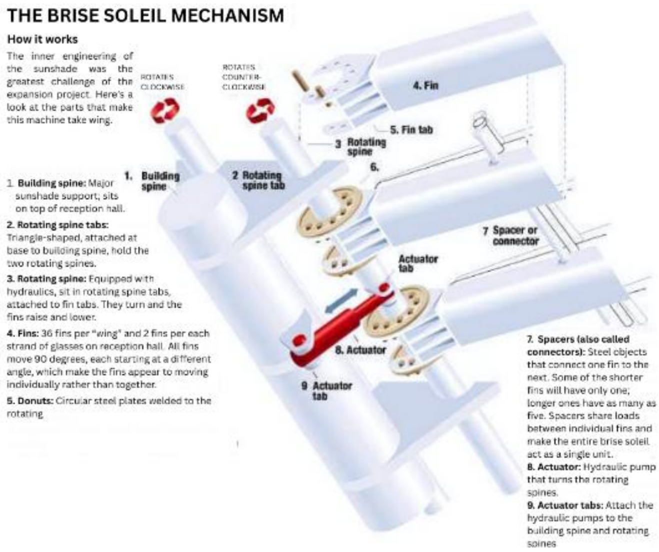

Image 6. Frame Detail of Quadracci Pavilion
(Source: Ebook Milwaukee Art Museum, 2015)

One of its most prominent features is the Burke Brise Soleil, a secondary skin system shaped like bird wings that can open and close automatically to respond to external climate conditions. This system not only functions to regulate lighting and protect from direct sunlight but also serves as an architectural symbol reflecting a philosophy of environmentally responsive design (Ciftcioglu & Yildiz, 2021; Salim & Burry, 2017).

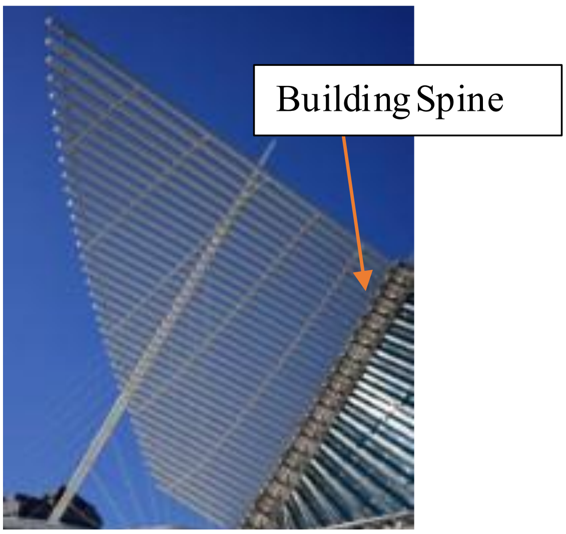

Image 7. Quadracci Pavilion Frame
(Source: Website, 2022)

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The main structure of this system consists of the building spine, the primary structural backbone supporting the entire mechanism, and a rotating spine that acts as the axis of rotation for the shading fins. These fins are made of a lightweight metal material, aerodynamically designed to reduce wind resistance and regulate light entering the building. Each fin is connected to a system of bearings and hydraulic actuators that allow for precise and simultaneous rotational movement.

The movement of these fins is controlled by environmental sensors that detect various variables such as light intensity, wind direction and speed, and ambient temperature (Alawaysheh et al., 2023; Wu et al., 2022). Light sensors based on LDR (Light Dependent Resistor) or photodiodes automatically trigger the movement of the actuators when sunlight reaches a certain intensity threshold.

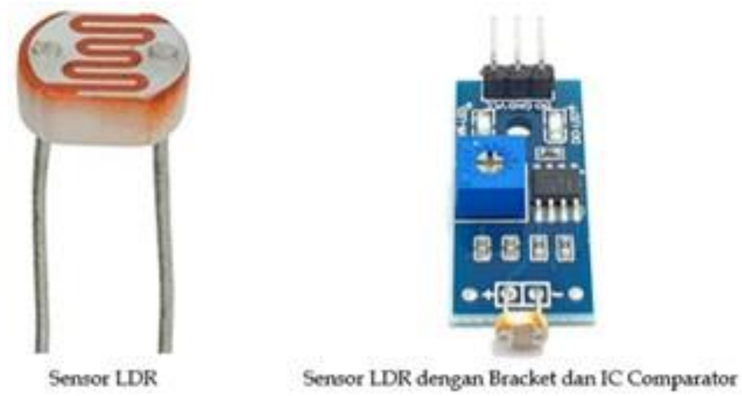

Image 8. LDR and Bracket Device
(Source: Website, 2024)

Meanwhile, wind sensors will activate a protection mode if the wind speed exceeds 37 km/h (Zarei et al., 2021; GhaffarianHoseini et al., 2020).

Image 9. Detail Image of Wind Sensor
(Source: Google, 2023)

The hydraulic actuator element plays a crucial role as the primary driver, generating sufficient linear or rotational force to move the large metal fins. This mechanism allows for stable control of movement even in extreme weather conditions, ensuring the system's responsiveness and safety (Heidari Matin et al., 2023).

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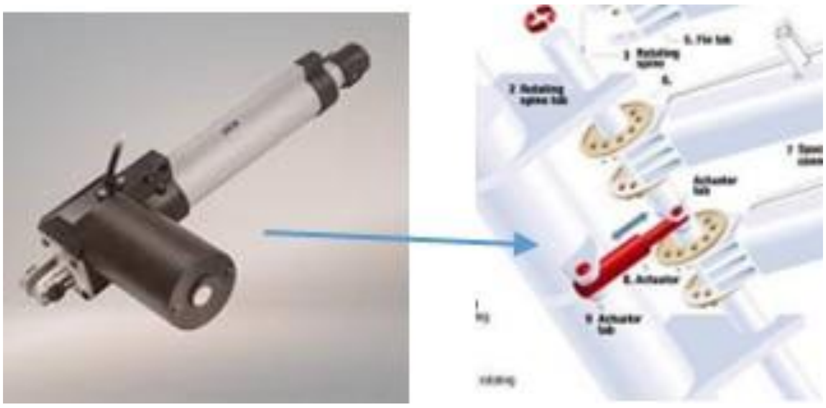

Image 10. Detail Image of Hydraulic Actuator
(Source: Website, 2024)

The entire system is controlled by an integrated Building Management System (BMS), which is responsible for monitoring and coordinating all adaptive activities, including the movement of the Brise Soleil, temperature regulation, lighting, and building maintenance systems (Carlucci et al., 2024). The system is even equipped with internal diagnostic sensors that detect hydraulic pressure, vibrations, temperature, and mechanical wear, allowing for early diagnosis of potential technical issues (Yadav et al., 2020).

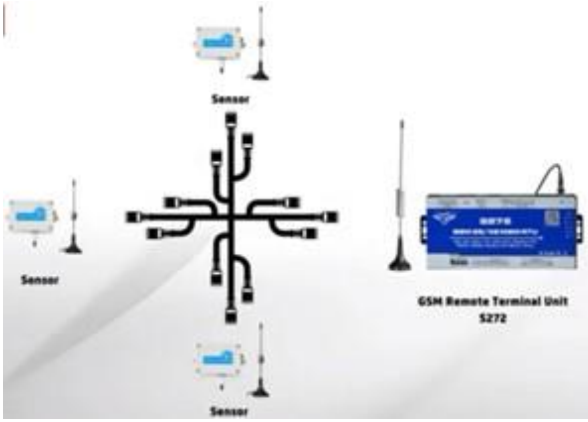

Image 11. Internal Diagnostic Sensor Diagram
(Source: Google, 2024)

The building's structure supports design efficiency and flexibility. It uses a combination of lightweight steel and slender reinforced concrete, which allows for large spans without central columns, creating a vast and open atrium space (Cheng et al., 2019). The exterior facade, dominated by glass, is equipped with a UV filter to screen out ultraviolet radiation, helping to reduce the thermal load on the interior and maintain visual comfort and energy efficiency (Jafari et al., 2021). The indoor lighting system is even controlled by natural light sensors, which adjust the intensity of interior lights based on the availability of light from outside, thus significantly supporting energy savings (Rahmani & GhaffarianHoseini, 2022).

Overall, the Brise Soleil is not just a shading system but has evolved into an architectural element that is active, adaptive, and integral to the building's performance. Recent research proves that dynamic facades like this can reduce a building's thermal load by up to 30–40%, enhance visual comfort, and extend the life of interior elements by protecting them from direct sunlight (Fathullah et al., 2021; Ghoneim, 2025; Nourian et al., 2023). At the same time, an automatic lubrication system and the modular design of some of its

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components also reduce the need for manual maintenance, reinforcing the principle of long-term efficiency.

The Quadracci Pavilion stands as concrete proof of how modern architecture can transcend aesthetic boundaries to become a smart, performative system. The integration of mechanical, sensory, and structural elements not only enhances the building's form but also improves its responsiveness and energy efficiency. In the context of urban tropical climates like in Indonesia, a similar approach could inspire the development of adaptive secondary skin systems tailored to local character, while integrating smart technology for the sustainability of future architecture (Putra et al., 2022; Lathifah et al., 2021; Kwon et al., 2023).

4) Potential Application and Challenges of Adaptive Secondary Skin in Indonesia

The application of adaptive secondary skin in Indonesia holds immense potential, considering its tropical climate characteristics of being hot, humid, and exposed to intense sunlight throughout the year. This system can provide both passive and active solutions for managing natural lighting, cross-ventilation, and indoor temperature control. By utilizing adaptive technologies such as weather sensors, automatic actuators, and responsive materials, buildings in tropical regions can significantly improve energy efficiency, especially in reducing the cooling load of spaces (Aldhaher & Selçuk, 2024; Naboni & Paoletti, 2021). Furthermore, the integration of a secondary skin can also extend the lifespan of the core building materials by protecting them from direct exposure to extreme weather and UV radiation.

4. CONCLUSION

The study of the Quadracci Pavilion at the Milwaukee Art Museum demonstrates that an adaptive secondary skin is not merely an additional layer but an integral system that harmoniously combines thermal function, lighting control, architectural expression, and smart technology. The implementation of a dynamic system like the Burke Brise Soleil allows the building to respond to weather conditions in real-time, significantly reduce energy loads, and create a more comfortable and inspiring spatial quality. This adaptability not only enhances the building's environmental performance but also strengthens its visual and symbolic identity within the urban architectural context.

These findings affirm that adaptive secondary skins have great potential for development in urban tropical regions like Indonesia, which face challenges of extreme climate and urban density simultaneously. The integration of environmental sensors, automated control systems, and the exploration of contextual forms and materials can support the creation of smart buildings that are both energy-efficient and visually aesthetic. Therefore, research and implementation of adaptive secondary skins should be continuously encouraged as an architectural approach for the future—one that is not only efficient but also living, responsive, and in harmony with environmental dynamics and human needs. Furthermore, for its application in Indonesia, it is recommended not just to mimic forms but to adapt the principles of integration by utilizing local materials and cultural contexts. A realistic and phased technological approach, supported by incentive policies, can accelerate the adoption of this type of architecture to realize future buildings that are efficient, responsive, and sustainable.

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