Analysing the Intelligent Building Skin Details Through Case Studies

Seval Doğan

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Approval of the Institute of Graduate Studies and Research

Prof. Dr. Ali Hakan Ulusoy
Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science in Architecture.

Prof. Dr. Rafooneh Mokhtar Shahi Sani
Chair, Department of Architecture

We certify that we have read this thesis and that in our opinion it is fully adequate in scope and quality as a thesis for the degree of Master of Science in Architecture.

Prof. Dr. Sadiye Müjdem Vural
Supervisor

Examining Committee

1. Prof. Dr. Sadiye Müjdem Vural
2. Asst. Prof. Dr. Nazgol Hafizi
3. Asst. Prof. Dr. Öznem Şahali Kovancı

ABSTRACT

In recent years, global problems such as rapid urbanization, population growth, and environmental degradation have highlighted the need for sustainable energy use and the integration of renewable resources in the building sector. Since a significant portion of global energy consumption occurs in buildings, intelligent building skins have become increasingly important in terms of energy efficiency and environmental awareness. These systems are not only designed to reduce energy loss but also to adapt to external environmental conditions and even contribute to energy generation.

This study aims to analyse building skins based on intelligent building design criteria and to investigate how these criteria are applied under different functional conditions while keeping climate as a constant variable. To ensure comparable external conditions, four case studies were selected, all located within Europe's temperate climate zone. These include two office buildings (The Edge – Amsterdam and Cube Berlin – Berlin), a residential building (BIQ House – Hamburg), and an experimental botanical garden structure (FlectoLine Façade – Freiburg).

The analysis was conducted using a comparative framework derived from literature-based intelligent design criteria. Key criteria such as human comfort, energy efficiency, cost, environmental impact, safety, durability/maintainability, sustainability, and intelligence/adaptivity were evaluated. In addition, the integration of smart technologies, including sensors, IoT, BMS, and renewable energy systems, into building skins was examined.

The findings of the study aim to reveal how different building functions influence the design and performance of intelligent building skins, while also highlighting their contribution to sustainable architecture and providing guidance for future design decisions and research.

Keywords: Intelligent Building, Intelligent Building Skin, Intelligent Building Design Criteria, Adaptive Building Skin, Energy Efficiency.

ÖZ

Son yıllarda artan nüfus, hızlı kentleşme ve çevresel bozulma gibi küresel sorunlar, enerjinin sürdürülebilir kullanımı ve yenilenebilir kaynakların yapı sektörüne entegrasyonunun gerekliliğini ortaya koymuştur. Küresel enerji tüketiminin büyük bir kısmı binalarda gerçekleştiğinden, akıllı bina kabukları enerji verimliliği ve çevresel duyarlılık açısından giderek daha önemli hale gelmiştir. Bu sistemler, yalnızca enerji kayıplarını en aza indirmekle kalmayıp aynı zamanda dış çevre koşullarına uyum sağlayabilen ve hatta enerji üretimine katkı sunabilen yapılar olarak tasarlanmaktadır.

Bu çalışma, bina kabuklarını akıllı bina tasarım kriterlerine dayalı olarak analiz etmeyi ve bu kriterlerin iklimin sabit bir değişken olarak tutulduğu farklı fonksiyonel koşullar altında nasıl uygulandığını araştırmayı amaçlamaktadır. Karşılaştırılabilir dış koşulların sağlanması için, tamamı Avrupa'nın ılıman iklim kuşağında yer alan dört vaka çalışması seçilmiştir. Bunlar; iki ofis binası (The Edge – Amsterdam ve Cube Berlin- Berlin), bir konut binası (BIQ House – Hamburg) ve deneysel bir botanik bahçesi yapısı (FlectoLine Façade – Freiburg) olarak belirlenmiştir.

Analiz, literatüre dayalı akıllı tasarım kriterlerinden türetilen karşılaştırmalı bir çerçeve kullanılarak gerçekleştirilmiştir. İnsan konforu, enerji verimliliği, maliyet, çevresel etki, güvenlik, dayanıklılık/bakım kolaylığı, sürdürülebilirlik ve zekâ/uyarlanabilirlik gibi temel kriterler değerlendirilmiştir. Ayrıca, sensörler, IoT, BMS ve yenilenebilir enerji sistemleri gibi akıllı teknolojilerin bina kabuklarına entegrasyonu da incelenmiştir.

Çalışmanın bulguları, farklı bina fonksiyonlarının akıllı bina kabuklarının tasarımını ve performansını nasıl etkilediğini ortaya koymayı, aynı zamanda bu kabukların sürdürülebilir mimarlığa katkısını vurgulamayı ve gelecekteki tasarım kararları ile araştırmalara rehberlik etmeyi amaçlamaktadır.

Anahtar Kelimeler: Akıllı Bina, Akıllı Bina Kabuğu, Akıllı Bina Tasarım Kriterleri, Uyum Sağlayabilen Bina Kabuğu, Enerji Verimliliği.

DEDICATION

To my family, to my professor for unwavering belief in me, and to my friends and colleagues who told me "keep going." Without you, this work would not have been possible.

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INTRODUCTION

Environmental problems and the weakening of ecological systems currently threaten the global environment. The question of whether current resources will remain in the future is examined from various viewpoints (Bekler et al., 2022). In addition, with the rise of urban development, increasing population, diverse human needs, and advancing technology, the question of maintaining a comfortable life has become more important (Dikmen & Gültekin, 2009). In this regard, the idea of sustainability ensuring a balance that supports human needs while protecting nature has gained importance in the field of architecture (Bekler et al., 2022). Buildings consume large amounts of energy and significantly contribute to global climate change and other environmental problems related to energy use. As these impacts become more widely recognized, it is increasingly important to integrate environmental performance into the building design process (Wang et al., 2005). The widespread acceptance of sustainability at the societal level in many countries has led to the emergence of concepts such as energy-efficient building design, intelligent buildings, and intelligent building skin (Dikmen & Gültekin, 2009). Especially intelligent building design and one of its core components, intelligent building skins, have the potential to enhance energy performance by adapting to changing environmental conditions. These systems are conceived not merely as passive skins, but as dynamic elements that guide and optimize energy flows (Esgil & Yamaçlı, 2023).

Although there has been growing interest in intelligent building technologies in recent years, there are still few comprehensive studies that systematically analyse building skins within a broad and integrated framework. Such analyses need to go beyond theoretical intelligent design criteria and include aspects such as control systems, sensor technologies, IoT, BMS integration, and the use of renewable energy systems.

By incorporating both functional and technological perspectives, this study aims to address this gap by examining contemporary applications. Conducting comparative analyses of buildings with different functional purposes, while keeping climate as a constant variable, provides valuable insights into how intelligent building skins operate under real-world conditions.

1.1 Problem Statement

In the context of evolving architectural technologies and intelligent building approaches, building skins represent critical elements such as structural innovations, advanced building management systems, and integrated renewable energy strategies. In order to understand the function and scope of intelligent skins, it is first necessary to clarify the concept of intelligent buildings (Böke et al., 2019). Taking this understanding into consideration, first of all, a literature review was made about intelligent building and intelligent building design criteria. While there has been growing research on intelligent building technologies, most studies focus on individual systems or components rather than providing a holistic evaluation of building skins. Moreover, many existing analyses are limited either to theoretical discussions or to case studies within a single climatic or functional context, which restricts their applicability to real-world design decisions.

There is a lack of comprehensive, comparative studies that examine intelligent building skins through both functional and technological perspectives. In particular, the integration of control systems, sensors, IoT, BMS, and renewable energy strategies into the design and operation of building skins has not been systematically evaluated. This creates a knowledge gap for architects, engineers, and researchers seeking to understand how different building functions and technologies interact to enhance performance.

To address this gap, this study investigates four case studies within the same climate zone but with different building functions. Through this approach, it aims to reveal how intelligent building skins perform under similar environmental conditions while serving diverse functional needs, providing a foundation for future adaptive and sustainable design strategies.

1.2 Research Aim

Awareness about intelligent buildings is increasing. Studies on this field try to draw more attention to this issue and encourage further research in this area. Because of the developing technology age, future trends will be towards structures that adapt to developing technology. The aim of this research is to analyse intelligent building skins by examining their design, performance, and technological integration under different functional conditions while keeping climate as a constant variable. The study seeks to provide a comprehensive understanding of how building skins contribute to sustainability, adaptability, and user comfort through the integration of intelligent technologies such as control systems, sensors, IoT, BMS, and renewable energy systems.

1.3 Research Objectives

To achieve the aim of this research, the study first focuses on understanding intelligent buildings by reviewing the literature on their definitions, characteristics, and technological components. This foundation provides the necessary context for examining intelligent building skins in greater depth. Based on this understanding, a comprehensive set of evaluation criteria is established, covering key aspects such as human comfort, energy efficiency, cost, environmental impact, safety, durability/maintainability, sustainability, and intelligence/adaptivity.

The study also evaluates the role of intelligent technologies including control systems, sensors, IoT, BMS, and renewable energy systems in enhancing the performance and adaptability of building skins. Following this, four case studies are analysed, all located within the same climate zone but serving different building functions, which ensures comparability in external conditions. Finally, the findings from these cases are compared to identify strengths, weaknesses, and lessons learned, providing valuable insights for the development of future adaptive and sustainable design strategies.

1.4 Research Questions

This study explores following research questions:

Main Research Question:

- How do different building functions influence the design and performance of intelligent building skins under similar climatic conditions?

Sub-Questions:

- How can intelligent building skins be systematically analysed using quality environmental modules?
- What role do intelligent technologies (e.g., control systems, sensors, IoT, BMS, renewable energy) play in improving building skin performance?
- What implications can be drawn from comparing different case studies?

1.5 Thesis Methodology

This thesis based on literature review. On account of this, the methodology of this thesis will be descriptive method and with help of this method provide data about intelligent building, features and components of intelligent building and intelligent building skin.

Data collection method will be based on qualitative research, provide information about two main topics of this thesis. First one, intelligent building design criteria and second one is building skin characteristics and classifications. After collect data for each research study, try to understand how to analyse intelligent building skin with help of findings.

Finally, this study, results will try to study cases and compare the results.

1.6 Limitation of the Study

While this study aims to provide a comprehensive comparison of intelligent building skins, several limitations were applied during the selection of case studies.

First, all selected projects are located within regions that share a temperate oceanic climate. This ensures consistency in environmental conditions and makes it possible to attribute performance differences primarily to building function and technology rather than external climatic variations. However, this also means that the findings may not be directly generalizable to buildings located in completely different climates, such as desert or tropical regions.

Second, the study is limited to medium-scale buildings. Only buildings between two and fifteen stories in height were considered, while very small single-story structures and extremely tall skyscrapers were excluded. This provided a more balanced comparison in terms of technical and operational priorities.

Third, only buildings that integrate renewable energy systems were included.

This criterion made it possible to evaluate both energy generation and building skin performance together. Buildings with fully passive skins or those without photovoltaic (PV) panels were excluded from the scope.

Fourth, a minimum level of smart system integration was required. Projects without sensors, automated control mechanisms, or digital monitoring systems were excluded because they do not fully represent the scope of intelligent building skin design. This limitation ensured that the study focused on buildings capable of data-driven performance analysis.

Fifth, recency of the projects was considered important. Only buildings constructed in 2010 or later were included to ensure that the findings reflect current technological developments and design trends. Older projects were excluded because their systems may not align with today’s standards or innovations.

Lastly, the study prioritized innovative and pioneering projects. For example, The Edge represents one of the most advanced office buildings with full IoT integration, Cube Berlin showcases a next-generation AI-based intelligent management system that seamlessly connects building operations with user interaction, BIQ House is the world’s first bio-reactive façade application, and FlectoLine demonstrates the latest adaptive façade prototype tested under real-world conditions. While other buildings in these regions also exist, they were excluded either because they had lower levels of technological integration or employed building skin strategies that were not directly relevant to the objectives of this study.

Chapter 2

INTELLIGENT BUILDING

2.1 Definition of Intelligent Building

Buildings are inherently linked to their usage and environment, and therefore their indoor environments are the results of a series of interactions influenced by daily and seasonal climatic changes. It is also affected by user needs, which can change depending on time and place. Over time, the world has begun to turn technology to create buildings that are more efficient, more operationally effective for their users, and more environmentally friendly (Himanen, 2003). Thus, it has led to the emergence of new concepts in field of architecture and construction, such as “smart” and “intelligent” buildings. Although the two terms are sometimes used interchangeably, they have different meanings.

According to the “Oxford Learner's Dictionaries” the adjective intelligent means

“ Good at learning, understanding and thinking in a logical way about things; showing this ability”. Smart means “quick at learning and understanding things; showing the ability to make good business or personal decisions”. For consistency, this thesis uses intelligent rather than smart. In the literature, intelligent building is often described as a systems-integrated approach that coordinates building services to improve occupant outcomes and resource use, whereas smart is commonly used for connected digital technologies and user-information functions.

Exploration of how buildings can exhibit intelligent and learning entities of the buildings arise from the concept of integrated building and machinery, this can be thought to have its earliest origin described by Le Corbusier a house as “a machine for living in” in his 1923 book Vers une Architecture (Towards a New Architecture).

When the concept of intelligence is accepted as defined in the literature as the ability of a building to collect and respond to information, an opportunity arises that can limit the addition of additional sub-items to the definition of intelligence and enable future research (Buckman et al. 2014).

2.1.1 Early Definitions of Intelligence in Buildings

The phrase 'intelligent buildings' was first used in the United States in the early 80's. Intelligent Building Institution in Washington described an intelligent building as “An intelligent building is one which integrates various systems to effectively manage resources in coordinated mode to maximise: technical performance; investment and operating cost savings; flexibility.” (Clements-Croome, 1997).

Intelligent buildings are a single building or a building complex, enable building occupants and managers in terms of cost, environmental control, security, and communication. These communication systems also provide connection with municipal authorities such as police, fire department and hospitals. It also designed as an ergonomic environment for building occupants, offering sophisticated computer and telecommunications services. Design covers a wide perspective, from the building scale at the macro level to the interior equipment at the micro level (Finley et al. 1991).

Intelligent buildings are flexible structures capable of adapting to various conditions. Clements-Croome (1997) illustrates this concept with the example of igloos, which can be considered intelligent buildings for the Eskimos. Due to their form and construction, igloos effectively respond to the specific climatic conditions of their environment, creating a comfortable space for their users. However, their performance is limited when faced with more variable or changing environmental conditions.

As a result, the term intelligent building was first introduced in the United States in the early 1980s. According to the Intelligent Building Institution in Washington, an intelligent building is defined as a structure that integrates various systems to effectively manage resources in a coordinated way, with the aim of maximizing technical performance, cost efficiency, and flexibility (Clements-Croome, 1997). This definition provides the conceptual foundation for this thesis, as it emphasizes the integration and coordination of systems, which are essential for analysing intelligent building skins through intelligent building design criteria. Additionally, Clements-Croome (1997) highlights the importance of adaptability by using the example of igloos, which effectively respond to specific environmental conditions but lack the flexibility to perform well under more variable circumstances. This perspective underlines the need for building skins that can dynamically adapt to changing environmental factors.

2.1.2 Understanding Intelligent Buildings

Intelligence will play an important role in building designs in the future; however, the concept of intelligence can be supported by the smart building, which has been used more in the literature lately. Smart buildings are intelligent buildings but with additional integrated elements such as adaptive control, enterprise, materials and construction. In smart buildings, four methods used to meet the drivers to building progression are developed in parallel and the information obtained from one area is used in the functioning of other areas. This differs from Intelligent Buildings, where intelligence is generally developed independently of other methods (Buckman et al. 2014).

The intelligent building approach covers the entire life cycle of a facility: it begins with early design decisions, continues through long-term operation and maintenance, is upgraded over time through the integration of new technologies, and extends to eventual decommissioning. Setting the “intelligent” goal at the start of design is like committing to an investment that promises high performance and value; once this decision is made, the architectural and engineering processes can proceed as usual.

These buildings are designed for low environmental impact and long service life through careful choices in materials, construction, operation, and maintenance. Integrating control systems, optimizing operations, and enabling enterprise-level management significantly reduces energy use and costs compared to non-intelligent buildings (Fratu & Fratu, 2012).

2.2 History of Intelligent Building

In conditions where environmental awareness did not yet exist, the destructive impact of energy consumption was ignored for a long time after the industrial revolution on the socio-cultural and scientific basis (Utkutuğ, 2001).Technological developments that occurred with the “Industrial Revolution” in the 19th century; It has enabled the formation of new architectural styles and materials in the field of construction and architecture. This situation gave rise to the “High-Tech Architecture” movement in the 20th century. This style, defined at “High-Tech Building' 87 Conference” in London. The main idea of high-tech buildings is showing and praise the technology (Zağpus, 2002). This development, in addition to positive developments, led to large energy losses and caused energy crises and cost increases in 1973-74 and 1979 (Günaydın & Zağpus, 2003). Since the years following the industrial revolution, with the development and widespread use of mechanical systems, design and providing of interior comfort based on the evaluation of climatic data in buildings have been abandoned. Following the energy crisis in the 1973s, it was realized in the 1980s that ecological problems based on environmental pollution and fossil-based energy resources were reaching their limits (Utkutuğ, 2001). The concept of information technologies (IT) emerged as a result of the second industrial revolution. This concept has led to concept of Intelligent Buildings (IB) in the 1980s. In order to reduce energy use, electrical and mechanical systems were first developed and new building products were used in the 1980s (Dayangaç, 2005). Accordingly, concepts such as “energy efficient design” and “intelligent buildings” have begun to enter into architecture (Günaydın & Zağpus, 2003). In North America, this idea began to be established in architecture in 1985, with articles titled “Intelligent Buildings in the Business World” published in magazines such as Forbes, Fortune and Business Week. Since this date, the latest technologies have begun to be used in new buildings for easier marketing (Dayangaç, 2005). In general, with the integration of research and approaches on energy-ecology and technology into our lives, intelligent building solutions that benefit from technological advancements have not only provided the opportunity to capture the ability to change and adapt, but also made it easier to take great steps in the context of ecology and energy (Utkutuğ, 2001).

2.2.1 The First Intelligent Building

The first intelligent building, called “City Place”, was built by Technologies Corporation in Hartford, Connecticut, between 1981 and 1983 (Figure 1). Figure 1 illustrates the vertical organization of intelligent buildings and how different systems operate together. As shown, security, communication, climate control, fire detection, energy efficiency, and automation systems are integrated within the structure. On the upper floors, smoke and heat detectors, alarm systems, and door alerts provide fire safety, while communication infrastructure, emergency lighting, and security systems ensure building safety. In this way, the building can give early warnings against potential risks and enable rapid response. Communication and data systems are supported by telephones, two-way communication infrastructure, and sound and image recording systems. In addition, a data shaft ensures uninterrupted data transfer between floors, while commercial data paths serve office needs. This structure represents the digital backbone of future intelligent buildings. Looking at vertical circulation systems, elevators are organized in separate shafts for upper and lower floors. A freight elevator is also included for material transport. Elevator machine rooms are placed at different points to increase capacity and efficiency. In terms of climate control, programmable air-conditioning units, air dampers, and thermostats on each floor provide user comfort while ensuring energy efficiency. The central ventilation system manages overall pressure and temperature throughout the building. Finally, the building automation system manages all these components from a single centre. Control rooms, such as elevator monitoring, the fire command centre, and the computer command centre, coordinate both daily operations and emergencies. Data received from sensors is continuously monitored and analysed through remote data receiving panels. In short, this section demonstrates that intelligent buildings are not only defined by technological equipment but also by the integration of multiple systems working together to create efficient, safe, and sustainable environments.

After this building, the intelligent building concept began to spread, especially in North America. Particularly in the study titled “The Electrical Research Association (ERA) Technology” in England, a performance comparison of intelligent buildings based on user needs was made in America and England, and the issue of adaptation of different intelligent buildings to current and future user needs was examined (Zağpus, 2002). Overall, the evidence shows that adaptability to current and future user needs is the main differentiator, rather than the mere presence of isolated technologies. The biggest gains were achieved when commissioning processes, data integration, and user interfaces were handled well; when these elements were weak, the benefits were limited.

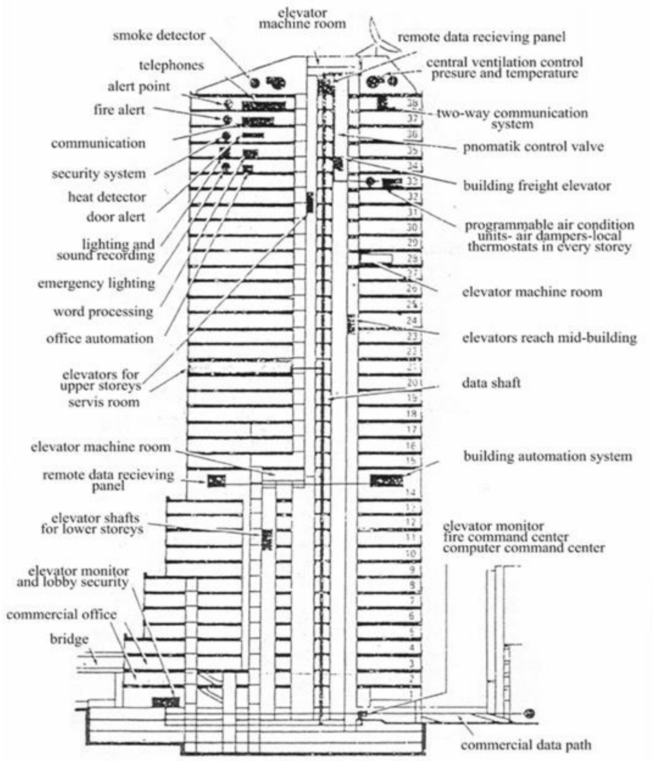


Figure 1: First Intelligent Building, Connecticut, USA, 1981 (Zağpus, 2002)

2.2.2 Evolution of the Intelligent Building Concept

Harrison, in his 1998 study presented the concept of intelligent building in three different categories; Automated Buildings, Responsive Buildings and Effective Buildings (Figure 1).

- **Automated Buildings (1981-1985)**

In the early 1980s, automatic buildings began to attract significant attention because they provided employment opportunities to a wider range of sectors compared to traditional buildings. During this period, distributing the load on user services, using main control computers in building management systems, and integrating small computers into security and monitoring systems became widespread. While the importance given to telecommunications infrastructure has increased, the security and reliability of decentralized information and voice transmission systems in North America were not sufficiently ensured (Harrison et al., 1998). In addition, Office Research into Buildings and Information Technology (ORBIT) research emerged and this research revealed that with the acceleration of technological developments, office buildings have been trying to adapt to this change, but some spatial inadequacies have occurred. The first ORBIT study was conducted in the UK in 1983 and it was emphasized that technology was playing an increasingly decisive role in office designs (Bernaden, 1988). The ORBIT 1 (1982-1983) study revealed how office design criteria's in the United Kingdom were shaped by information technologies, while the ORBIT 2 (1985) study was conducted in North America. These studies have revealed that different spatial organizations and various information technologies should be considered together when creating office spaces. At the same time, spatial change and adaptation requirements have been revealed in accordance with user needs.

The concept of automated intelligent buildings was rapidly adopted in Japan, leading to substantial investments in the sector. Japanese office buildings, which were behind western standards in the 1970s but with significant financial support from the Ministry of Construction, companies were encouraged to develop intelligent buildings. With these supports, the first intelligent building was built as the headquarters of Toshiba in 1984, followed by the headquarters of NTT in 1986 (Dayangaç, 2005).

- **Responsive Buildings (1986-1991)**

During this period, it was realized that technology alone could not provide the level of integration to meet user needs. While furnishing modifications and relation to fit out were crucial factor in terms of building life cycles, also responsiveness to change was important. Moreover, as the definitions of technological building intelligence proved to be inadequate, DEGW architects F. Duffy, P. Eley, L. Giffone, and J. Worthington conducted studies on transforming the work environment and integrating organizations within it to overcome the period's challenges (Zağpus, 2002).

According to Harrison (1998), intelligent buildings that support flexible use must be designed to meet users' changing needs and to adapt to environmental conditions like weather and natural surroundings.

- **Effective Buildings (1992-)**

Third generation intelligent buildings after 1992 are structures that are not only technology-oriented but also adapt to user and business needs. The main objectives of third-generation intelligent buildings include optimizing management processes with human-centred facility management systems and building automation systems, minimizing operating costs by effectively planning spatial changes, and strengthening business management by facilitating information processing, storage, presentation, and communication (Zağpus, 2002).

Different approaches were used to create the IB concepts in different periods. For instance, China's IB sector began in the 1990s, although Japan and Britain embraced the IB concept in the 1980s. Japan designed some of the most technologically developed IBs in the world during this time. For instance, Nippon Telephone Telegraph (NTT) Twins (1986) in Tokyo, Toshiba Headquarters (1984), etc. (Harrison, et al, 1998).

While there was a transformation focused on the internet and informatics in the early 21st century, today, new technologies such as artificial intelligence, big data, the internet of things (IoT) and smart materials have become decisive in building design and use. Buildings are no longer equipped with only digital systems; they are becoming structures that increase environmental sustainability, can adapt by anticipating user needs and maximize energy efficiency. In Figure 2, the evolution of the intelligent building concept is summarized.

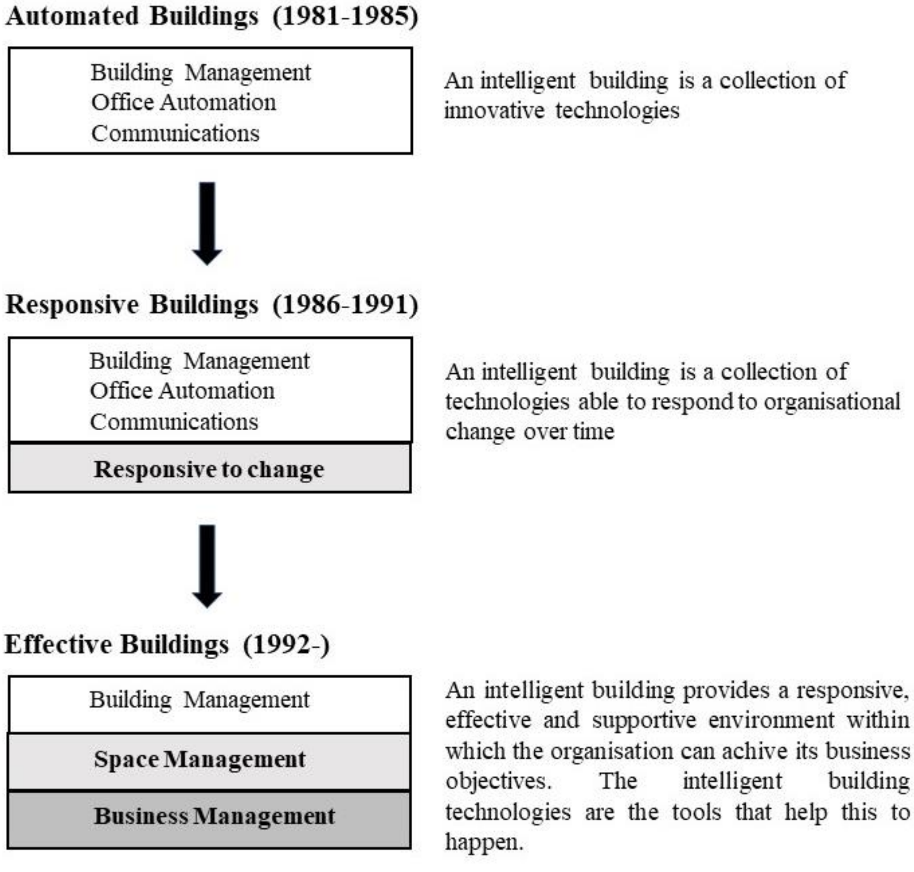


Figure 2: Evolution of The Intelligent Building Concept (Harrison et al. 1998).

2.3 Intelligent Building Design Criteria

IBs are characterized not only by their technological components, but also by the ways in which they address user demands, environmental concerns, and operational efficiency.

2.3.1 Quality Environment Modules (QEMs)

The discovery and use of Quality Environment Modules (QEMs) is the foundation of one of the first organized methods for evaluating intelligent buildings. These modules, which were created to direct the design and operational decision-making process, include essential topics including cost effectiveness, user comfort, space flexibility, and environmental friendliness.

The following are the 10 key modules of intelligent buildings, which are called "Quality Environment Modules (QEM)":

M1: environmental friendliness– health and energy conservation;

M2: space utilization and flexibility;

M3: cost effectiveness– operation and maintenance with emphasis on effectiveness; M4: human comfort;

M5: working efficiency;

M6: safety and security measures– fire, earthquake, disaster and structural damages, etc.

M7: culture;

M8: image of high technology;

M9: construction process and structure

M10: health and sanitation (Omar, 2018).

The 10 key modules mentioned above constitute the basic level of the definition of intelligent building. Based on these basic level, the concept of intelligent building is redefined as follows:

"An Intelligent Building is designed and constructed based on an appropriate selection of quality environment modules to meet the user's requirements by mapping with the appropriate building facilities to achieve long-term building value" (So et al., 1999, p. 488). This new definition of the concept of intelligent buildings is based on a two-dimensional structure: the needs of building developers, owners, or users (deliverables) and the technologies that enable these needs to be met (systems and services). The integration of these two dimensions aims to provide measurable benefits to the building, such as increased productivity, market value, and energy savings. With this approach, each building type may require different design criteria to qualify as an intelligent building. The types of buildings considered within the scope of intelligent buildings can vary in function, including housing, industrial buildings, commercial buildings (offices or retail), transportation terminals, educational facilities, public service buildings (such as libraries or community centres), and religious buildings. Accordingly, different modules can be assigned to each building type based on their level of priority (P1 being the highest, P8 the lowest). Table I presents examples of how these modules are prioritized for four different building types (So et al. 1999).

Table 1: Prioritization of Quality Environment Modules (QEM) Based on Building Type (So et al., 1999).

Type of building	P1	P2	P3	P4	P5	P6	P7	P8
Hospital	M1	M6	M4	M5	M3	M7	M2	M8
Residential	M4	M7	M6	M1	M3	M2	M5	M8
Commercial (office)	M5	M2	M1	M4	M3	M7	M6	M8
Transportation terminals	M6	M4	M1	M8	M7	M3	M2	M5

Table 1 shows that the top priority module for hospitals is M1, which focuses on environmental friendliness, health, and energy saving; M4, which represents human comfort, is the priority for residential buildings; M5, which emphasizes work efficiency, stands out in office buildings; and M6, the security and safety module, takes first place in transportation terminals. This systematic approach provides a fundamental roadmap for developing intelligent building designs that are aligned with specific building functions.

In this context, modules for different building types can be combined in various ways based on different priority levels. Once a module is selected, a number of predefined building facilities associated with it are also assigned. Whether the designer includes all of these possibilities in the project depends on two main factors: the first is the priority level of the module in relation to the building type; the second is the availability of financial resources (So et al. 1999).

Recent review work by Tahmasbi et al. (2025) synthesizes advanced decision-making frameworks for skin design, combining MCDM, performance simulations, and life-cycle assessment. As summarized in Fig. 3, these studies converge on six key factors guiding skin choices: sustainability/energy efficiency, cost, occupant comfort, environmental conditions, regulatory requirements, and the interactions among them. This set aligns closely with the QEM perspective articulated above: sustainability and energy efficiency correspond to M1; cost maps to M3; occupant comfort to M4; regulatory requirements are reflected in M6 (safety/security) and M9 (construction process/structure); and environmental conditions act as the contextual driver through which M1 and M4 are realized. Moreover, the reviewed frameworks emphasize adaptability in response to changing climate and user needs an aspect that reflects M2 (space utilization/flexibility) and reinforces performance targets across M1–M4.

Figure 3: Key Factors in Building Skin Decision- Making

As a result, the building skin-oriented literature and the building-level QEM framework rest on the same performance base. Building on this alignment, the next subsection outlines Omar's (2018) analytical, multi-layer classification that links these priorities to enabling technologies.

2.3.2 Analytical Classification and Multi-Layer Evaluation

Omar in 2018 presented a classification structure that includes the basic level components for the architectural definition of the concept of intelligent buildings, based on the Eight Quality Environment Modules (QEM) developed by (So et al. 1999) (Figure 4). In this classification, prominent titles such as Building Management System (BMS), Building Automation System (BAS), sensors, smart materials, intelligent skin/interactive facades and passive design techniques are included. This structure provides a decision-making mechanism to support the project teams' primary goal of reducing energy consumption through the efficient use of available resources while maintaining a high quality of life.

Figure 4: Intelligent Buildings Criteria Selection with Main Factors (Omar, 2018)

Finally, Omar in 2018 gives in Figure 4 that the main factors that make up the definition of an intelligent building are divided into secondary subheadings aimed at optimizing energy consumption. At this level, many elements such as interactive facades, intelligent building skins, BAS, BMS, sensors, environmental techniques, renewable energy systems are among the evaluation criteria. Additionally, defined the third and most detailed stage of the intelligent building assessment criteria, the “core level.” This level includes 64 parameters and ensures that the basic and secondary levels work together in harmony, supporting a design goal that reduces energy consumption, produces clean energy and reduces CO_2 emissions.

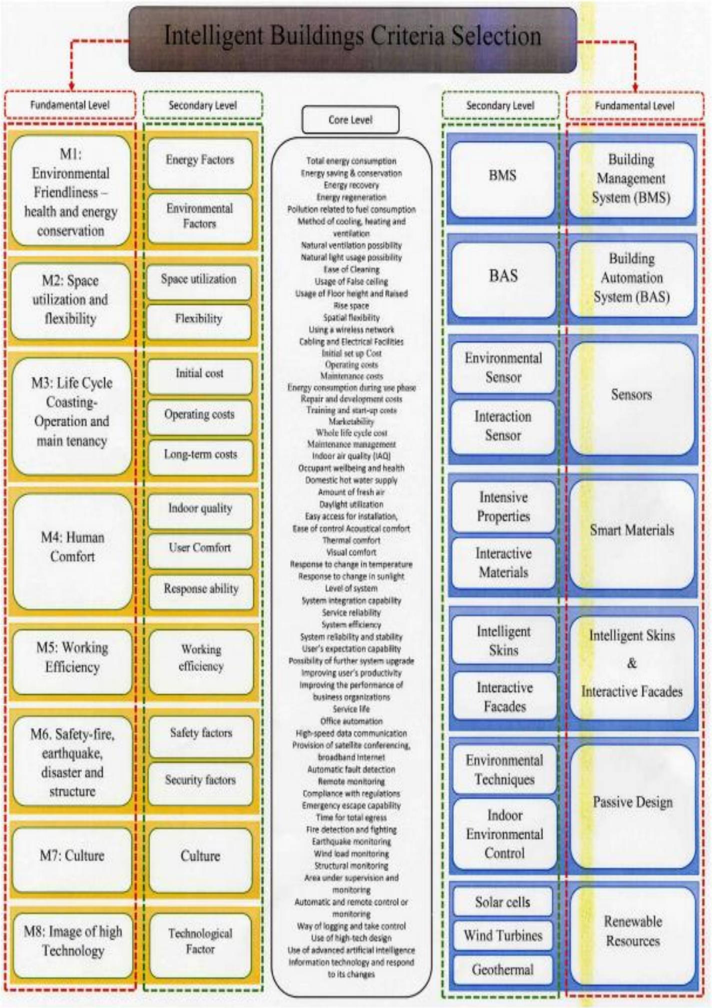


Figure 5: Merging Several Criteria from Several Point of View in One Diagram (Omar, 2018).

QEM modules (e.g., environmental friendliness, comfort, efficiency, safety) provide a functional lens for classifying building needs. So et al. in 1999 defined these modules and introduced a functional prioritization across different building types. Omar in 2018 expanded the framework from eight to ten modules and strengthened its practical use by linking each module to technological enablers (BMS, renewable energy, IoT/sensors, etc.).

2.3.3 From IB Design Criteria to IB Skin Design Criteria

Building skin systems are an essential component of intelligent buildings and play a central role in passive solar architecture. They reduce energy for heating, cooling, and lighting, support natural ventilation, and enhance indoor comfort. Because outdoor conditions are variable, fixed-feature skins tend to raise energy use and impair comfort, leading to lower productivity and greater environmental pollution. Accordingly, adaptability to environmental change should be a core design criterion (Gün & Aygün, 2008).

As technology advances, performance expectations for building skins continue to increase. Their primary function is to shield the structure and its contents from harsh conditions extreme temperatures, precipitation, wind, humidity, and solar radiation (Moghtadernejad et al., 2018). To limit the harmful effects of overheating, glare, and reflection on the building skin, computer-controlled blinds (shades), shutters, and protective canopies recognized as energy-absorbing elements are among the most common solar-control methods (Erturan, 2010). In intelligent buildings, energy-efficient and intelligent skin systems are often configured as double-skin façades to meet diverse comfort needs (Boduroğlu & Seçer Kariptaş, 2010).

Beyond energy, considerations should include user comfort (acoustics, indoor air quality, thermal and visual control), energy performance, environmental impact, safety, durability, and sustainability (Moghtadernejad, 2013). In such skins, a building management system supported by sensors and actuators manages energy flow to maximize efficiency, enabling dynamic responses to climate, user needs, and occupancy (Ljubenović et al., 2018). When integrated with sensors, automation, and passive/active energy solutions, the skin not only protects the building but can also support energy production. Renewable systems such as solar and photovoltaic panels turn the skin from a static barrier into a dynamic, responsive element (Radwan, 2017).

While intelligent systems can be retrofitted, the preferred approach is to integrate them from the design stage. Nevertheless, full energy efficiency is unattainable without passive design criteria. Without strategies like solar orientation, natural ventilation, thermal mass, and active building skin design, one cannot fully claim user comfort and energy efficiency (Sev, 2009, as cited in Erturan, 2010).

The analysis criteria used in this study were developed by combining different theoretical frameworks from the literature. Figure 3, which presents the Key Factors in Building Skin Decision-Making, largely overlaps with the Quality Environmental Modules (QEM) approach. The criteria shown in this figure Sustainability, Cost, Occupant Comfort, Energy Efficiency, and Environmental Conditions form the core evaluation parameters used in this thesis. In addition, some QEM criteria introduced by So et al. (1999) and later classified as Fundamental Level by Omar (2018) in Figure 5, which are not present in Figure 3, were also included in this study. While most of the criteria in this figure align closely with those in Figure 3, two additional modules Safety and Image of High Technology were integrated into the analysis. The Safety criterion was added because of its critical importance in addressing structural security and user protection. The Image of High Technology module was redefined in this study as Intelligence (Adaptivity), reflecting the innovative, smart, and adaptive characteristics of building skins. This redefinition allowed these dynamic and responsive features to be evaluated under a separate criterion.

Furthermore, the Durability/Maintainability criterion is directly linked to the Life Cycle-based evaluation approach within the QEM framework. This connection emphasizes the long-term performance of the building skin, considering factors such as durability, maintenance needs, and overall lifespan, which are essential for sustainable performance. As a result, by combining the elements of Figure 3 and Figure 5, a comprehensive final set of criteria was developed for this thesis. This integrated approach enables a multidimensional evaluation of building skin performance, supporting both passive and active strategies within a unified and holistic framework.

Chapter 3

INTELLIGENT BUILDING SKIN

3.1 General Definition of Intelligent Building Skin

3.1.1 From Wall to Façade: The Evolution of Building Skins

The form and function of contemporary wall and facade systems are the result of a long process that has evolved side by side with that of human history, based on the requirements of settled and nomadic existence. In settled life, one of the two main solutions shaped by various dwelling forms and influenced by climatic conditions, massive walls immovable and designed for long-term use were employed; whereas in nomadic life, façade methods that provided mobility and adaptability were employed (Knaack et al., 2007). Construction systems since the beginning of the 20th century have especially made glass a major building component; the façade has begun to be considered not only as a boundary but also as a dynamic surface that establishes a relationship with the environmental context.

The use of glass in the 20th century played an important role in almost completely reversing the forms of the Middle Ages. The use of glass in buildings has increased rapidly since the Industrial Revolution. It has transformed from solid-walled structures created from small openings into transparent surfaces consisting of minimal materials cladding the skeletal carrier frames and cores. In addition, the pioneers of modern architecture used glass as a fundamental tool in creating new spatial dynamics. One important example of this transformation is Mies van der Rohe’s skyscraper proposal in 1921 and buildings like the Crystal Palace. These examples show that glass became not just a material, but also an architectural concept. This change laid the foundation for rethinking the building envelope with more complex and multi-functional terms like “skin” (Davies & Rogers, 1981).

3.1.2 General Definitions

- **Facade**

The facade in architecture refers to the principal face of the building's entry, and its specifics vary depending on the community and culture in which it is located. The façade is often seen as the part of a building that interacts directly with its urban surroundings. The building's front, which reflects its purpose, provides insight into the cultural context of the building's construction. Historical settings known as “facades” are where cultures' cultural shifts can be viewed from a new perspective. As a result, it is particularly crucial to protect historical buildings' façade and restore them as closely as possible to their original state. As a consequence, the structures' social and cultural sustainability is provided. Each countries has its unique buildings and styles that exhibit periodic variations (Arslan & Yıldırım, 2021). Technological advances created a new trend in facade design during the last 70 years (Heidari Matin & Eydgahi, 2019). Technological progress in computer engineering, control systems, AI, cybernetics, and material science enables the integration of systematically dynamic components into building façades (Pask, 1969). Using dynamic systems in façade design has strengthened the relationship between the building, its users, and the environment.

The technologies applied allow façade systems to adapt continuously, changing their behavior or structure based on both environmental inputs and the evolving needs of the users (Heidari Matin & Eydgahi, 2019).

Facades can also have practical and functional purposes, creating a safe interior environment in line with the needs of building occupants. Architectural design necessitates structural realization in addition to the concept and composition of space (Knaack et al., 2012). The exterior of a building provides shelter for its users. It also protects both the building users and the internal structure from external factors such as rain, wind, snow, heat, cold, noise and humidity, so there is an important relationship between the facade and the building occupants (Şener, 2006). The word facade derives from the Vulgar Latin word facia, meaning “face”, and passed into English via Italian (faccia) and French (façade). It was originally used to refer to the front of a building, which is the “face” of the building; this usage is sometimes continued today (Merriam-Webster, n.d.). In addition to its literal meaning, the façade is often understood as the building’s surface that connects the inside with the outside environment. Architecturally, the term usually indicates the front face seen from the street or within the urban context (Şener, 2006).

- **Envelope**

The building envelope is probably the oldest and most primitive architectural element (Semper et al., 2004). It embodies the distinction between interior and exterior, natural and artificial; it separates the private from the public and land ownership; and when transformed into a façade, the building envelope functions as a representational tool in addition to its basic environmental and territorial roles (Zaera-Polo, 2008).

The building envelope is one of the basic external elements in terms of the functionality of the building. Also, the envelope not only defines the aesthetic identity of a building, but also contributes significantly to its energy performance and interior usability. With technological developments, new improvement options that can be integrated into the facade are emerging and the performance of the building envelope is being improved in this direction (McFarquhar, n.d.). The building envelope is designed as a system in which each component contributes to specific performance elements such as thermal insulation, moisture control and aesthetic expression.

Figure 6 shows a typical timber building envelope section in which each layer performs specific functions in the building envelope system.

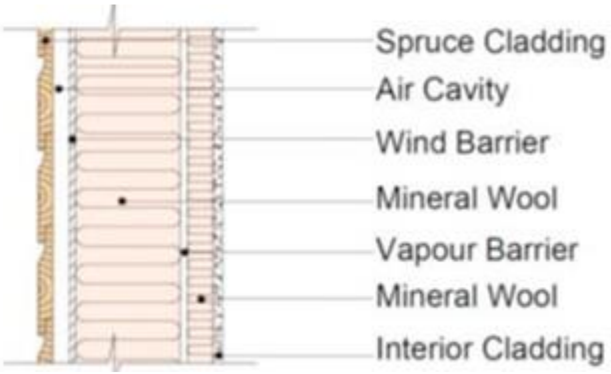


Figure 6: A Typical Timber Building Envelope Section (Gradeci et al., 2018).

- **Curtain Wall**

In the 1920s, curtain wall systems became a distinctive element reflecting the ideals of modern architecture (Huxtable, 1957). In Walter Gropius's design, the curtain wall became a defining element of his architectural approach and over time became one of the symbols of the International Style (Mislin, 2009).

Curtain walls are systems that do not directly contribute to the building's load-bearing system and consist of independently created frame elements (Cucuzzella et al., 2023).

Curtain walls fulfill two basic functions: to create a protective layer against external factors (e.g. air and water leakage) and to allow light to pass into the interior McFarquhar, n.d.). A curtain wall is a lightweight exterior construction system, usually made of industrial components such as glass and metal. It is located in front of the main structure of the building; it is quick to install, transparent and does not affect the interior space (Mijovic et al., 2018).

- **Surface**

One of the concepts associated with the facade in contemporary architectural discourse is “surface” (Leatherbarrow & Mostafavi, 2002). The architectural shell is related to both the structure and surface of the building. Building exteriors, create environmental impact regardless of the material used and generate spatial effects through which the materiality of architecture communicates. In this way, buildings express both their identities and their relationships with the environment through their surfaces (Goldsmith, 2011). In addition, envelope and external wall of the building remain their importance as basic external elements in terms of the functionality of the building. In contrast, the aesthetic appearances of the façade are expressed mainly through the outermost layers: the surface and the skin (Cucuzzella et al., 2023).

- **Building Skin**

The term skin was originally introduced to distinguish between the building's cladding and its supporting skeleton (Cucuzzella et al., 2023). The main function of human skin is to separate and protect the organism from the environment (Gruber & Gosztonyi, 2010), while at the same time creating a reactive interface that constantly collects data by sensing stimuli such as heat, pressure, humidity and pain (Lupton, 2002). Inspired by human skin, the concept of “building skin” defines the holistic envelope of a building, whether inside or outside, regardless of wall or roof distinction. This layer no longer serves purely as a structural element but instead takes on a functional, interactive, and almost organic character. Its early examples emerged as part of low-energy design approaches, featuring foldable or sliding shutters and adjustable louvers. Over time, it has evolved to incorporate a wide range of mechanisms such as shading, glare control, light redirection, and thermal or energy management enhancing both performance and adaptability (Del Grosso & Basso, 2010). According to Wigginton and Harris (2002), the building skin becomes an envelope that self-balances interior-exterior conditions while carrying the multi-layered protection and perception functions of living tissue to architecture.

3.1.3 Understanding of Intelligent Building Skin

The word intelligent means a higher level of performance and organization than smart (Shahin, 2019). The intelligent building skin, which is a combination of elements that protect the structure from external effects, can be adjusted to maintain building comfort with minimum energy as environmental conditions change (Ljubenović et al., 2018). An intelligent building skin seeks to optimize the building's systems to the highest possible degree in terms of climate adaptation, energy use, and occupant comfort. The operational intelligence of these systems manifests through sophisticated sensing and decision-making processes. Building automation and physically adaptive components like sunshades, louvers, movable vents, or smart material assemblies are frequently used to achieve this. The system should possess intelligence and emergent capabilities; it must analyse and learn from occupant behaviour, anticipate forthcoming weather changes, and adjust itself accordingly (Shahin, 2019). Intelligent buildings are defined as structures that perceive external and internal environmental conditions, then decide how to act to create an appropriate and comfortable interior space, and respond quickly to user demands (Thun & Velikov, 2013). The building skin is incorporated into the building system and is managed by the central building management system by communicating with sensors and various actuators connected to the main control board (Wigginton & Harris, 2002). In this context, intelligent building skins are seen not only as passive elements that protect the structure from external factors but also as dynamic systems that improve energy efficiency, optimize user comfort, and respond proactively to environmental changes. This definition provides a conceptual basis for evaluating the selected case studies within the framework of intelligent building design criteria.

3.2 Intelligent Building Skin Classification

Intelligent building skins can be categorised into two principal typologies: single-skin and double-skin systems.

3.2.1 Single Skin Facade

A single skin façade is the fundamental means of enclosing a space. It typically comprises walls constructed from materials such as brick, stone, or prefabricated blocks with openings for windows and, where necessary, a roof that incorporates skylights. Adding a secondary layer to this façade enhances its thermal insulation, thereby reducing cooling demand in summer and heating demand in winter (Kumar & Raheja, 2016).

3.2.2 Double Skin Facade

Double-skin façade (DSF) is a façade solution that has evolved from the past to the present and is used as a multi-layered “second skin” in contemporary architecture (Kumar & Raheja, 2016). In this regard, double skin facade is a design component that aims to improve the performance of the building to respond to different needs (Cucuzzella et al., 2023). This architectural approach began in Europe and has quickly spread worldwide (Hilmarsson, 2008). The use of a double skin façade system in buildings supports sustainable architecture, aims to reduce energy consumption, and provides higher thermal and visual comfort (Kumar & Raheja, 2016). According to Çakır (2011), the double-skin façade system features an outer and inner layer, separated by an air space that usually measures between 20 centimetres and 2 meters.

The outer layer insulates the building from external environmental conditions while allowing air and light to enter in a controlled manner. Thus, when the windows in the inner layer are opened, fresh air enters the space, natural ventilation and daylight are provided; unwanted heat gain-loss and external noise are minimized. In addition, even in high-rise buildings or windy locations, the inner windows can safely remain operable, which maintains natural airflow. Because the cavity stores passive heat or coolness, the demand for mechanical systems is reduced; consequently, operating costs fall and the building's overall sustainability improves. The system can be diversified by configuring the air cavity in different ways. For instance, as box window façade, shaft box window façade, corridor façade, or multi storey double-skin façade (Kumar & Raheja, 2016).

- **Box Window Façade**

The façade is segmented horizontally and vertically, creating independent "window boxes." This arrangement delivers high levels of thermal and acoustic insulation and is the only method that offers both functions simultaneously on façades with conventional rectangular openings. It is also widely used in renovation projects to improve building performance and makes it easier to add a double-skin façade to existing structures (Kumar & Raheja, 2016).

Figure 7: Example of Box Window Façade (Begeç & Savaşır, 2004 as cited in Kızıltoprak, 2019).

- **Shaft Box Window Façade**

This system is based on the box-type window. It consists of independent horizontal box window units with a vertical shaft. It collects solar radiation, benefits from chimney-effect ventilation and provides a high level of sound insulation. The shaft can be used as a natural or mechanical airflow system. However, in practice, this type of construction is best suited to low-rise buildings, as the chimney height is necessarily limited (Kumar & Raheja, 2016).

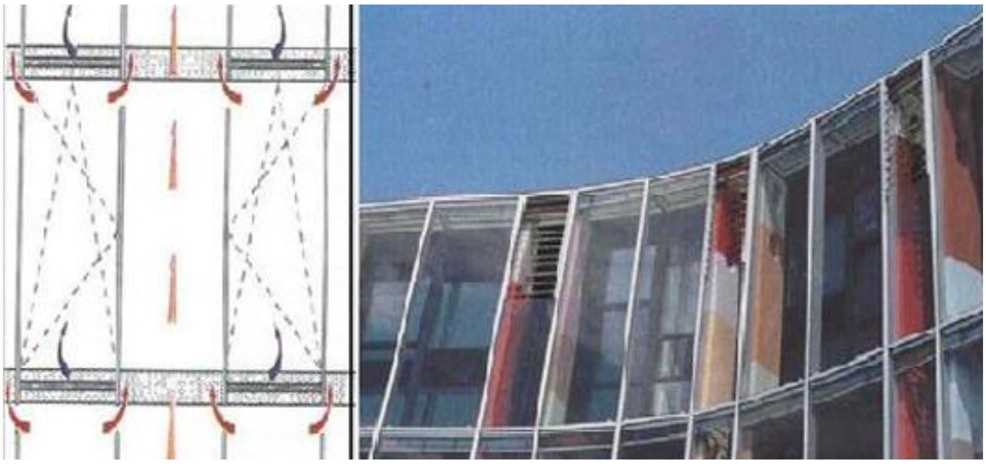


Figure 8: Example of Shaft Box Window Façade System (Begeç & Savaşır, 2004 as cited in Kızıltoprak, 2019).

- **Corridor Façade**

The air cavity between the outer and inner façades is horizontally divided by each floor slab and is wide enough to allow access for maintenance and service operations. Ventilation can be either natural or mechanical, and the air-intake and exhaust openings in the outer skin are positioned close the floor and ceiling levels. This corridor-type façade layout places no restrictions on building height (Kumar & Raheja, 2016).

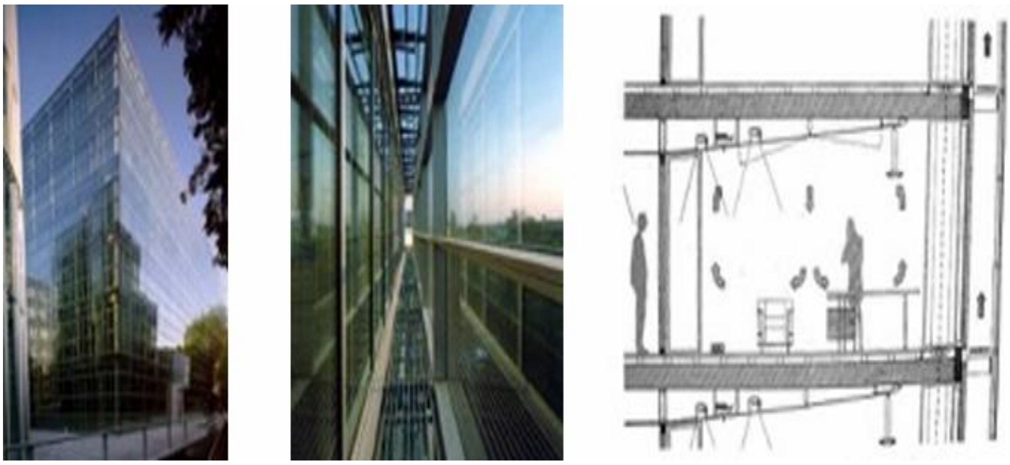


Figure 9: Victoria Life Insurance Building is an Example of A Corridor Façade (Compagno, 1999 as cited in Boduroğlu & Seçer Kariptaş, 2010).

- **Multi Storey Double Skin Façade**

There is no partition between the two skins; the cavity is ventilated through large openings at the base and roof. Combining corridor and shaft–box concepts, the façade supplies fresh air in winter and exhausts warm air in summer. It works well in areas with high external noise, requires no extra vents along its height, and can serve as a common air duct for multi-storey buildings (Kumar & Raheja, 2016).

Figure 10: Example of Multi Storey Double-Skin Facade System (Sharma, 2003 As Cited In Boduroğlu & Seçer Kariptaş, 2010).

3.3 Intelligent Building Systems

3.3.1 Control Systems

Effective control plays a crucial role in ensuring the successful performance of intelligent building skins. Control types are divided into two categories: extrinsic and intrinsic (Loonen et al., 2013).

Intrinsic control means that the “smart” of the system is built into the material itself. When an environmental trigger like surface temperature or solar radiation appears, the system reacts on its own. This open-loop type uses smart materials such as thermochromic, photochromic, or phase-change materials (PCMs) and needs no outside intervention (shown with dashed arrows in Figure 13).

Extrinsic control, on the other hand, works with a feedback or closed-loop setup that combines sensors, a processor, and actuators. Electrochromic glazing, movable shading devices, and kinetic façades belong to this group. Because they read environmental data and respond accordingly, they are called intelligent systems (shown with solid arrows in Figure 13) (Loonen et al., 2017).

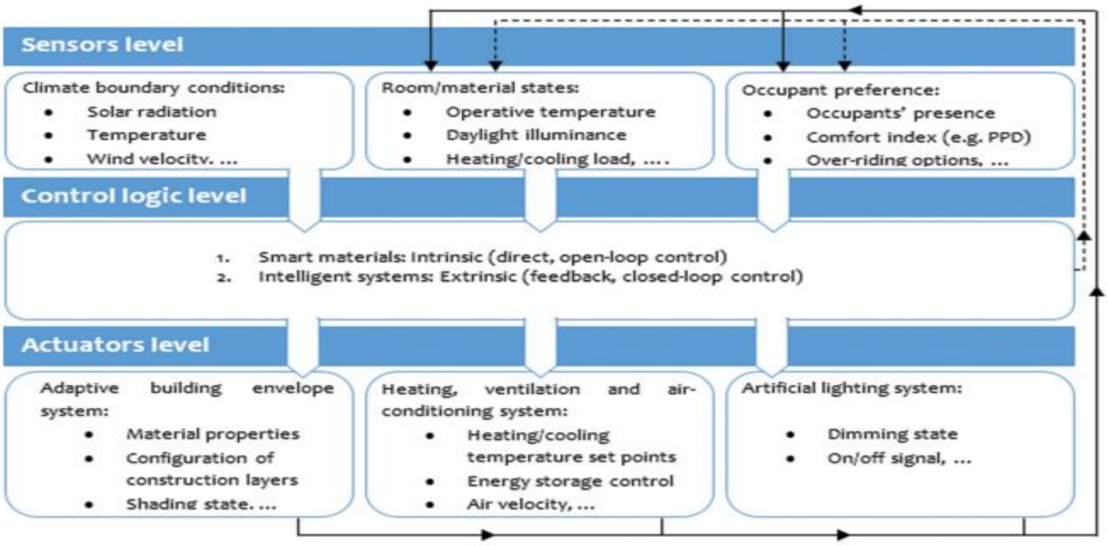


Figure 11: The Control Scheme for Building Services and Adaptive Façades Uses Two Kinds of Lines: The Solid Line Shows Active, Closed-Loop Control, While The Dashed Line Shows Passive, Open-Loop Control (Loonen et al., 2017).

In an open-loop setup, the input is processed and a command is sent to the actuator, yet the system has no built-in feedback to verify whether the action was carried out.

A closed-loop system includes extra features that check whether the commanded action really happened. For instance, a door opener may use a limit switch to confirm the door is fully open, or a slider could have a sensor verifying it moved 25 mm. The feedback is sent to the controller, which compares the initial command with the final state. If the task failed, the system can try again, show an error, or choose another action. While these feedback loops usually rely on microprocessors, past automation proves that mechanical solutions can also provide closed-loop control (Addington & Schodek, 2005).

Figure 12: Concept of Open Loop System (Modin, 2014).

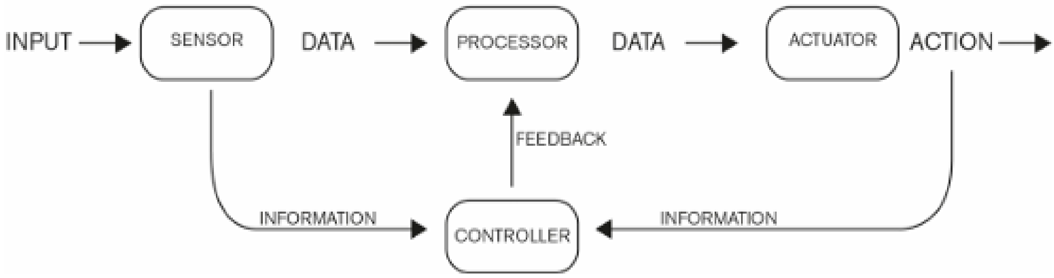


Figure 13: Concept of Close Loop System (Modin, 2014).

As shown in Figure 12, open-loop systems collect data from sensors, transmit this data to a processor, and then convert it into action through actuators. However, since there is no feedback mechanism in this process, the accuracy or effectiveness of the action taken is not verified (Modin, 2014). This system essentially operates on a one-way flow, where responses to environmental conditions rely solely on predefined commands. The Kiefer Technic Showroom building is a concrete example of this structure. The building’s façade consists of 112 aluminium panels that automatically open and close throughout the day in response to the movement of sunlight, regulating the interior temperature and lighting balance (Ayyappan & Kumari, 2018).

These panels are managed by a central control system and can also be manually operated by users. However, the system does not verify whether the panel movements are executed correctly through feedback. This demonstrates that the Kiefer Technic Showroom features a dynamic building skin operating on an open-loop control logic.

Figure 14: Kiefer Technic Showroom (Ayyappan & Kumari, 2018).

As shown in Figure 13, close-loop systems operate based on a feedback mechanism, allowing them to respond to environmental changes in real time. In these systems, data collected from sensors is not only processed but also used to verify the accuracy of the actions taken, making adjustments whenever necessary (Modin, 2014).

Al Bahar Towers serves as a concrete example of this concept. The building’s façade system continuously monitors environmental conditions using sunlight, wind, and rain sensors. Each unit of the façade is managed by control software that tracks the sun’s movement, with positioning sensors embedded in every actuator. The system provides constant feedback to the operator on wind speed, light intensity, rainfall levels, and the folding status of the panels. Through this feedback, the façade operates not only according to pre-programmed scenarios but also adapts to real-time conditions. For instance, in the event of a sudden storm, the system automatically moves the panels to a safe position to protect the building (Karanouh & Kerber, 2015). These features demonstrate that the dynamic surface of Al Bahar Towers is equipped with a true close-loop control mechanism.

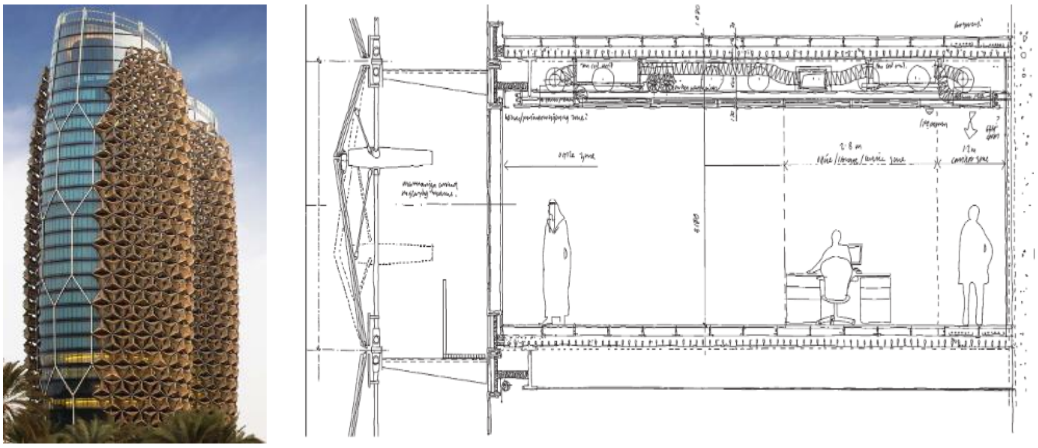


Figure 15: Al-Bahr Towers (Karanouh & Kerber, 2015).

- **Sensor Technologies**

The word sensor comes from sense, meaning to detect something (Addington & Schodek, 2005). Sensors detect physical factors like heat, light level, or movement and produce a signal that changes according to how strong the factor is. In the same way, receptors in our fingers sense surface roughness, temperature, and pressure (Zeqiri & Luma, 2008). A sensor touches the stimulus directly and always involves changing or passing energy from one form to another. It also gives an output signal that can later be read for measurement or control. Sensors come in many forms, including light, sound, thermal, humidity, touch, position, proximity, motion, chemical, magnetic, basic, environmental, and biosensors types.

Light Sensors: Light sensors use the electrical signal generated by light falling on semiconductors. Photodiodes provide digital output to the microprocessor; phototransistors work like switches, generating voltage depending on the amount of light; LDRs change resistance according to the light. In infrared sensors, an IR LED/laser source and a photodiode/photoresistor receiver work together to detect reflected IR light.

Sound Sensor: The most common type of sound sensor is based on piezoelectric material. The pressure created by acoustic waves generates mechanical force in the piezoelectric material, producing a measurable electric current; the microphone detects this current.

Thermal Sensor: Devices such as thermometers, thermocouples and thermistors are used to measure thermal changes. Thermistors change their resistance in a predictable way as the temperature changes; this resistance difference is measured in circuits and converted into digital output.

Humidity Sensor: In humidity measurement, the classical psychrometer determines relative humidity using the temperature difference between ‘wet’ and ‘dry’ thermometers, while modern sensors monitor electrical property changes in moisture absorbing materials.

Touch Sensor: Touch sensors are devices that react by detecting physical contact. The simplest types are mechanical switches that switch an electrical circuit on and off. More advanced models use capacitive sensors that measure the electric field interaction between two conductive surfaces.

Position Sensor: Position sensors measure the location, orientation and speed of movement of an object. Many different technologies are used for this purpose, whether mechanical, optical, inductive or capacitive based. In addition to position and speed sensors, this group also includes force or pressure sensors, mechanical deformation sensors (e.g. strain gauges) as well as vibration and acceleration sensors.

Proximity Sensor: Proximity sensors can be used in a wide variety of ways to indicate whether a physical element is close to another element; numerous examples of this can be seen in industrial machinery, but also in some simple door closing devices. These sensors mostly detect the presence of the object, not its range.

Motion Sensor: Motion sensors are mostly based on infrared (IR) technology; they detect the temperature difference created by a moving object relative to its surroundings and trigger an alarm when the balance between the two areas they monitor in cones is disturbed.

Chemical, magnetic and other basic sensors: Chemical sensors contain substances that react with certain chemicals in the environment and produce a colour change (e.g. litmus paper) or an electrical signal. Magnetic field sensors react in a similar way with electrical signals.

These sensors are often used in industrial processes and environmental monitoring systems. Devices that detect air pollutants can measure gases such as hydrocarbons, ammonia, sulphur dioxide and some have replaceable sensors. Specialised monitors have been developed for specific gases such as carbon dioxide. They can also be integrated with temperature and humidity sensors. Similar systems are also used in water pollution monitoring and often work in conjunction with flow meters.

Environmental Sensor: Environmental assessments are based on understanding existing conditions and monitoring how they change over time. For this purpose, various sensors have been developed to measure data such as temperature, humidity, air movement, gas and particle density. Although these sensors, most of which can record data, have different measurement types, their common purpose is to monitor environmental changes.

Biosensors: Biosensors are sensors that contain or react to a biological element. A historical example is the canaries that accompanied miners. While traditional chemical analyses are time-consuming and complex, biosensors measure in real time without the need for sample collection. This fast and direct approach has made biosensors one of the fastest growing areas of the sensor industry (Addington & Schodek, 2005).

As a result, sensors translate physical, chemical, and biological phenomena into readable signals, enabling measurement, control, and real-time decision making. From light and sound to humidity, motion, environmental, and biosensing, each class relies on a specific transduction principle yet serves the same goal: turning changes in the world into actionable data.

As an example, the dynamic facade system of Al Bahar Towers in Abu Dhabi operates through integrated sensors designed to optimize sunlight and heat gain. Light, wind, and rain sensors control the real-time opening and closing of the triangular modules on the exterior. These sensors enable the system to respond instantly to environmental conditions and switch to a safe mode during extreme situations, such as storms. As a result, the facade not only enhances energy efficiency but also supports user comfort and building safety.

Figure 16: Al Bahar Towers. Dynamic Facade Modules with Integrated Light, Wind, and Rain Sensors for Real-Time Environmental Response. (Karanouh & Kerber, 2015).

- **Processor**

In control systems, the processor is the central unit that receives data from sensors, analyses this information based on specific algorithms, and generates decision-making outputs for other components such as actuators. In open-loop systems, the processor reads environmental data only at the beginning and produces fixed commands without any feedback mechanism. However, in closed-loop systems, the process becomes more complex: the processor takes into account the feedback provided by the controller and adjusts its outputs according to the current situation. This allows the system to operate adaptively in response to changing conditions (Loonen et al., 2013; Modin, 2014).

In intelligent building applications, the processor plays a key role within Building Management Systems (BMS) by managing components such as HVAC, lighting, and shading systems. Through this control, it contributes to the optimization of both energy efficiency and indoor comfort (Minoli et al., 2017). Therefore, the processor is not only a unit that processes data but also serves as the core decision-making element that shapes the intelligence of the entire system.

- **Actuator**

Actuators are parts that move systems or mechanisms in machines. These parts need a control signal and an energy source to operate. Control signals can be electrical, hydraulic, pneumatic or even human powered. These signals are sent by software, robotic, mechanical or human-managed systems. Actuators are guided by the control system according to environmental information from sensors. After receiving the control signal, they convert this energy into physical movement, creating linear or rotational movements. They can use sources such as hydraulic fluid, electricity or air pressure. Actuator types are divided into 3 as electrical, hydraulic and pneumatic actuators. Electrical actuators work with electricity, while hydraulic actuators are used in work machines or factories that require high power. Pneumatic actuators work with air pressure and can be used in rotary or vacuum systems. Electrical types are more common in daily use, while pneumatic and hydraulic types are more common in industry and production, where more force is needed (Goyal et al., 2021).

- **Feedback**

Providing information to users through feedback can have a major impact on building related outcomes. Users get feedback by interacting with the building or by directly experiencing the results of actions (e.g. noticing warm air or hearing the system switch on and off). This feedback experiences help users to learn, understand, interpret, comment, motivate and interact more effectively with the building. Depending on the context and available technology, the information can be shared visually, through sound, or by touch. Especially in systems that respond slowly such as thermal systems, feedback plays a key role in how users perceive, interact with, and stay involved in sustainable strategies for building use (Day et al., 2020).

3.3.2 Internet of Things (IoT)

IoT is a system of interoperating networks of smart things that can be identified and addressed. These ‘things’ can be physical objects, their data, or the relationships between them. Usually everything is considered a network node. IoT systems can grow from small structures with a few sensors to very large systems. In these systems, nodes can be of different types, such as sensors, actuators, gateways or virtual objects, and they all work in continuous connection. In addition, the use of interface functions offered by objects is also seen as an important development (Minerva et al., 2015).

Sensors collect and send real-time data about their surroundings. Controllers use this data to respond quickly and to plan long-term actions (Yaïci et al., 2021). IoT-enabled building skins can adjust weather changes and user preferences to keep indoor spaces comfortable. Thus, the desired temperature is provided indoors and energy is used more efficiently (Li et al., 2019). Real-time control of indoor conditions makes sure that people stay comfortable (Yaïci et al., 2021). IoT sensors can find faults in the skin system, so repairs can be done quickly (Qiang et al., 2023). Also, data from sensors can be studied to see patterns and make better building designs and operations (Li et al., 2019). As an example, figure 17 and figure 18 illustrate the advanced IoT integration at *The Edge* building. The IoT infrastructure includes IP-addressable LED luminaires, the Mapiq mobile application, and smart lockers by Vecos, which together form a connected digital ecosystem. As shown in Figure 18, the Mapiq interface allows users to interact with the building in real-time, managing tasks such as space reservations and environmental adjustments. Floor-level zone controllers provide localized management and enable rapid fault detection, while operational data is visualized through dashboards powered by Mapiq and Schneider Electric using Power BI. This system allows the building to continuously monitor both external environmental conditions and user preferences, ensuring real-time optimization of lighting, HVAC, and shading operations, as represented in Figure 17 (Jalia et al., 2019).

Figure 17: The Edge Building in Amsterdam (PLP Architecture, n.d.).

Figure 18: Mapiq Interface Used at The Edge (Jalia et al., 2019).

3.3.3 Building Management System (BMS)

Building Management Systems (BMS) are important for improving energy efficiency in buildings. These systems integrate various technical components to monitor and manage HVAC, lighting, and other building operations. They also allow for continuous adjustments based on energy use patterns, occupancy, and environmental data simulations (Liang & Wang, 2024). In addition, Building Management Systems (BMS) can also manage functions such as security, access control, and fire detection when integrated with Internet of Things (IoT)-enabled systems. These systems are typically accessible remotely. The benefits expected from intelligent buildings depend on integrated and software-supported energy management. BMS solutions enable automation both at data collection and measurement points. By combining sensor data from different areas such as energy, lighting, and security, BMSs can analyse usage trends either directly or through cloud-based tools. This makes the system more flexible and efficient (Minoli et al., 2017). Although BMS were originally developed to monitor and manage a building's energy needs, their role soon expanded to include building skins with kinetic elements that influence thermal performance, such as heat loads. With technological advancements like electronically controlled and mechanically operated shading and ventilation systems, BMS contributed to the rise of kinetic or dynamic façades, forming active and high-performance building skins (Harry, 2016).

As an example, Pearl River Tower, located in Guangzhou, China, is an iconic skyscraper designed with a strong focus on achieving high energy efficiency. The Building Management System (BMS) in this building manages various components such as lighting, HVAC, and façade shading systems through a single centralized platform. This system analyses real-time data collected from sensors to optimize energy usage and continuously improve indoor comfort (Aydinç, 2023).

For instance, façade shading elements and natural ventilation panels are automatically controlled through the BMS, regulating indoor temperature based on sunlight and wind conditions. This demonstrates how a BMS not only enhances energy efficiency but also plays a key role in ensuring the effective operation of the intelligent building skin system.

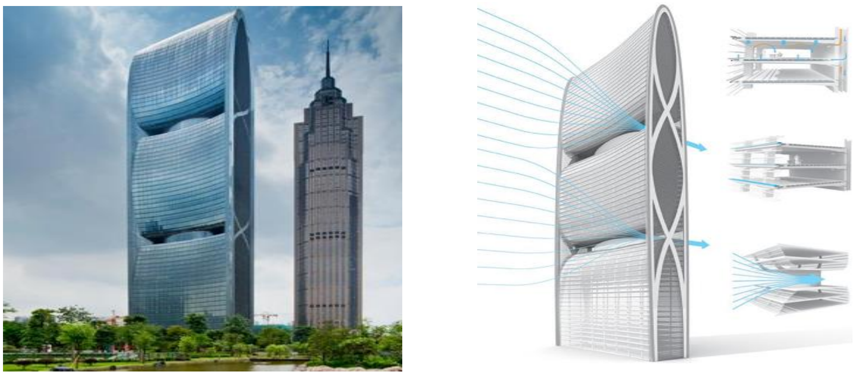


Figure 19: Pearl River Tower in Guangzhou, China (Aydinç, 2023).

3.4 Environmental Control & Energy Systems

3.4.1 Solar Collector & Photovoltaic Panels

Within the scope of active systems, buildings can be heated using solar collector panels, while photovoltaic (PV) and building-integrated photovoltaic (BIPV) panels are used to generate electricity from sunlight (Çelebi, 2002 as cited in Okumuş, 2020). One of the most prominent active systems is the photovoltaic (PV) system, which consists of solar cells that convert sunlight into electrical energy. A photovoltaic cell, also known as a solar cell, is a semiconductor device that directly transforms solar energy into direct current (DC) electricity. These PV modules can be integrated into a building's outer skin by replacing conventional components such as roofs, facades, parapets, railings, entrance canopies, or sunshades. In this way, energy production is combined with the functional design of the building skin (Altın, 2002, as cited in Koçu & Dereli, 2004). Located in South Korea, the Korean Tower reduces heating and cooling loads through its building skin, while also generating energy with the use of photovoltaic (PV) panels.

Figure 20: Korean Tower Example (Michler, 2010).

3.4.2 Solar Control Systems

Solar control elements reduce indoor glare and lower heating and cooling loads by partially or completely blocking direct solar radiation on the building skin. These elements can be placed on the exterior face, between the glass layers, or on the interior face of the building skin (Figure 21, 22). When installed outside, they intercept sunlight before it reaches the glass surface, making them effective in limiting glare and cooling demand; however, because they are exposed to weather, maintenance and repair costs are higher. External shading devices can be made of wood, metal, or plastic-based materials and can be designed as fixed or operable.

In double-skin façades, systems located in the cavity between the glass panes offer advantages: they do not occupy interior space, have more favourable maintenance costs, and are protected from environmental factors. In this arrangement, oblique rays enter the interior indirectly, while perpendicular rays are blocked. Therefore, geographic location and building skin orientation should be considered carefully, as spaces may overheat in summer and useful heat gains may be limited in winter. Devices placed on the interior may reduce usable space, but cleaning, maintenance, and repair costs are relatively low; however, because sunlight still reaches the glass surface, indoor temperature rise and glare can occur. These systems can be controlled automatically or manually (Okumuş, 2020).

Figure 21: Solar Control System on The Exterior Face of The Building Skin (Radwan, 2017).

Figure 22: Venetian Blinds Installed in The Cavity Between Glazing Layers (Loncour Et Al., 2005).

3.5 Materials and Glass Systems

With the development of glass technology, glazing systems have become components that adapt to changing environmental conditions to support user comfort and can adjust their optical properties either automatically or manually. In intelligent building skins, glass is typically considered in two categories: energy-efficient glazing and smart glass (Okumuş, 2020).

3.5.1 Energy- Efficient Glazing

Glass types that maintain their structural integrity while controlling sunlight and heat are commonly used in energy-efficient designs. To manage solar gain, heat-absorbing (tinted) glass and reflective glass are preferred. For climate control, low-emissivity (low-e) glass, spectrally selective glass, and insulated glazing units are used to improve thermal insulation (Okumuş, 2020).

- **Heat-absorbing (tinted) glass**

By adjusting the iron content in float glass or adding certain metal oxides, it is possible to produce glass in different colours. Compared to regular float glass, tinted glass absorbs more sunlight, which causes the surface temperature to rise. Therefore, in cases where solar control is important or the glass is used in large sizes, the glass should be tempered to reduce the risk of surface stress (Compagno, 2002, as cited in Okumuş, 2020).

- **Reflective Glass**

During or after production, the surfaces of reflective glass are coated with metal or metal oxides to give them properties that reflect more sunlight and allow less of it to pass through (Ünal, 2006, as cited in Okumuş, 2020). Since they allow only a small amount of sunlight to pass through, artificial lighting may be needed indoors to ensure user comfort (Okumuş, 2020).

- **Low-e glass**

Double glazing with low-e coatings offers advantages by allowing daylight and solar heat into the interior while reducing heat loss. However, depending on the geographic location, additional measures may be necessary. In mild and humid climates, low-e coating alone is usually sufficient, while in hot and humid regions, it should be combined with solar control coatings (Okumuş, 2020).

- **Spectrally Selective Glass**

Spectrally selective glass has the ability to control solar radiation by filtering one or more parts of the solar spectrum, such as visible, infrared, or ultraviolet light. Depending on their optical properties, different types of this glass can be selected for various climate conditions and building types. These coatings can be applied to clear or tinted glass surfaces. Since they can reflect shortwave infrared radiation from the sun and longwave infrared radiation between indoor and outdoor environments at different rates, they are commonly used in buildings to reduce heat loss and improve solar control (Ayçam & Utkutuğ, 1999).

- **Insulated Glazing Units (IGUs)**

This glass system consists of at least two glass panes, with a spacer bar, desiccant material, and insulating gas placed between them. The edges of the glass panels are sealed with airtight insulation to prevent air leakage. The space between the panes is filled with dry air or an inert gas to improve thermal and sound insulation (Okumuş, 2020).

3.5.2 Smart Glass

Smart glass refers to glazing that can dynamically change its optical properties in response to varying climatic conditions and adapt to both indoor and outdoor environments. Acting as a filter between interior and exterior spaces, it can be activated manually or through automatic control systems. Designed to manage the transmission of heat and light, smart glass can switch from fully transparent to fully opaque according to user preferences. Unlike blinds, smart windows preserve a clear view of the outside while partially blocking light. Types of smart glass include variochromic, electrochromic, gasochromic, thermotropic, PDLC (polymer-dispersed liquid crystal), thermochromic, and photochromic systems (Erturan, 2010).

3.5.3 Smart Materials

Smart materials are special building elements that can change their shape, colour, or properties in response to external factors such as temperature, light, electric fields, and movement. Because of these features, they can adapt to changes occurring both inside and outside the building. When used in the building skin, they support the structure in automatically adjusting to environmental conditions. This ability to adapt makes them essential for intelligent building skins (Jaffar et al., 2024).

- **Electrochromic and Thermochromic Materials**

Electrochromic technology offers new possibilities for controlling light and heat in buildings. Electrochromic glass can serve multiple purposes at the same time, functioning as glazing, a window, a curtain wall system, a lighting control device, or an automated shading system. These materials change their colour when an electric voltage is applied. Similar technologies include liquid crystals and suspended particle devices, which can adjust their transparency or colour when electrically activated. Electrochromism is defined as a reversible change in the colour of a material caused by applying an electric current or voltage. In practical terms, an electrochromic window can be darkened or lightened electronically. A low voltage makes the glazing darker, while reversing the voltage returns it to a lighter state. This effect is the result of a chemical change on the surface of the material, usually through oxidation-reduction reactions. In real-world applications, the transparency and colour tone of electrochromic windows can be controlled precisely with electrical input. However, to keep the window in a darkened state, voltage must be maintained continuously, which can be a disadvantage in terms of energy use and operational efficiency (Addington & Schodek, 2005). While electrochromic systems rely on electrical input for activation, another class of smart glazing thermochromic materials responds directly to temperature changes, offering a passive alternative.

Thermochromic materials are a type of smart material that can respond to changes in ambient temperature by altering their colour and light transmittance in a reversible manner. By absorbing heat, they undergo a phase change or chemical reaction at the molecular level, making them highly suitable for passive climate control strategies. For instance, thermochromic films can reflect solar radiation as temperatures rise, preventing overheating of interior spaces, while allowing more heat to pass through under cooler conditions, thus minimizing heat loss. These adaptive behaviours support energy efficiency and enhance thermal comfort when integrated into building skins.

However, despite their promising potential, thermochromic technologies face several limitations in practical applications. One major drawback is their lack of control in the visible part of the spectrum. Since heat is the activating input, thermochromic glazing functions most effectively in the near-infrared (NIR) range of the solar spectrum. As a result, the visual transmittance of these materials is relatively low and typically ranging between 27% and 35% which directly affects outdoor visibility and daylight access, two of the primary purposes of glazed façades. Therefore, the application of thermochromic materials in smart window systems remains limited, particularly in buildings where transparency and visual comfort are essential (Addington et al., 2005).

Consequently, both electrochromic and thermochromic glazing technologies contribute to energy efficiency and occupant comfort; however, electrochromic systems offer greater control and flexibility through electrical activation, while thermochromic systems provide passive operation but face limitations in visual transparency.

- **Phase Changing Materials (PCM)**

When a material experiences a change in temperature or pressure, it can transition from one state to another, a process called phase change. This process typically involves storing, absorbing, or releasing large amounts of energy as latent heat. Phase transitions such as solid-to-liquid or liquid-to-gas take place at precise temperatures, which are determined by the material's composition. Phase change materials are developed to utilize these heat absorption and release processes.

In the context of architecture, PCMs are integrated into building elements to help regulate indoor thermal conditions by storing and releasing heat at predetermined temperature thresholds. This capability contributes to improved thermal comfort and reduced reliance on mechanical heating or cooling systems. One of the earliest architectural applications was the development of "phase change wallboard," which incorporates embedded materials that enable phase change functionality within conventional wall systems (Addington & Schodek, 2005).

- **Self-Cleaning Coatings**

The concept of self-cleaning originated from research on the superhydrophobic properties of certain plant leaves. The lotus leaf is the most famous example, capable of shedding water droplets rapidly to achieve a natural cleaning effect. With a contact angle above 150° and a sliding angle below 2°, water droplets form spherical shapes due to high surface tension and roll off, taking dirt particles with them (Sherin et al., 2025).

In today's context of rapid urbanization, pollution, and dirt accumulation, self-cleaning materials and coatings have gained significant importance. Advances in material science have enabled the development of innovative, sustainable products that keep surfaces clean without harsh chemical agents, offering cost-effective maintenance solutions. These coatings help to reduce corrosion, lower water usage, minimize reliance on toxic chemicals, and decrease air pollution (Xu et al., 2016).

Integrating self-cleaning photoactive coatings into building façades not only lowers maintenance needs and provides long-term economic benefits for building owners and facility managers but also contributes to sustainable management of the built environment by reducing the environmental footprint of cleaning operations over the building's service life (Andaloro et al., 2016).

- **Bio-Inspired Materials and Bionic Skins**

Bio-inspired materials are developed by taking structural and functional inspiration from natural organisms. Their hierarchical architectures play a key role in achieving both high mechanical strength with low weight and functional properties such as superhydrophobicity, responsiveness to environmental stimuli, and structural color (Wang et al., 2020). Research shows that micro- and macro-scale structures in nature can be adapted for thermal regulation. For example, silkworm cocoon fibers provide passive cooling through broadband light scattering and mid-infrared emission, desert silver ant hairs reflect sunlight to manage heat, and polar-bear-inspired fiber networks offer effective thermal insulation. These biological strategies can be applied to building skins for radiative cooling, insulation, and light control (Ling et al., 2023).

In the context of bionic skins, these natural principles can be translated into architectural applications in various ways. Surface textures and geometries can be designed to provide self-cleaning and anti-soiling properties, reducing maintenance requirements. Smart coatings that respond to environmental changes such as light, temperature, or humidity can enable dynamic optical and thermal control. Additionally, photonic structural colour systems, inspired by biological organisms, can regulate daylight and solar gains without the need for conventional pigments.

By integrating these bio-inspired strategies into skin systems, it is possible to achieve reduced cleaning frequency, enhanced material durability, and significant energy savings through passive heat management. Furthermore, such systems can be manufactured on a large scale using modern production methods, including additive manufacturing (Wang et al., 2020; Ling et al., 2023).

In this chapter, the essential components and systems required in an intelligent building skin to ensure human comfort, energy efficiency, and advanced control have been examined. The discussion covered control mechanisms such as sensors, processors, actuators, and feedback loops, as well as IoT applications, building management systems, solar collectors, photovoltaic panels, smart glazing, and smart material solutions. Among these, some elements primarily contribute to energy efficiency (e.g., energy-efficient glazing, photovoltaic panels, phase-change materials), while others focus on improving human comfort (e.g., shading devices, humidity and temperature sensors, smart ventilation systems). A further group of components enhances the intelligence and adaptability of the building (e.g., IoT-based control systems, building management systems, bio-inspired), enabling more effective responses to environmental changes.

As highlighted at the beginning of this study, achieving the key criteria of human comfort, energy performance, and intelligence relies on the systems and components described in this chapter. In the following chapter, selected case studies will be analysed to demonstrate how these principles are applied in practice and how intelligent building skins perform in real-world examples.

Chapter 4

CASE STUDY: ANALYSIS OF INTELLIGENT BUILDING SKIN

The growing demand for energy, the impacts of climate change, and the depletion of natural resources are pushing the construction sector to adopt sustainable and innovative solutions. Since buildings account for a significant share of global energy consumption, reducing their environmental impact requires the implementation of new design strategies. In this context, intelligent buildings and especially intelligent building skins are gaining importance for their ability to save energy, enhance user comfort, and minimize environmental effects. Unlike static envelopes, intelligent skins are dynamic systems that can adapt to changing conditions, manage energy flows, and even generate energy when necessary.

Within the Quality Environmental Modules (QEM) framework, the key criteria defined for intelligent buildings such as comfort, energy efficiency, and adaptability are equally essential for intelligent skins. To meet these criteria, skins integrate technologies such as sensors, actuators, IoT-based control systems, building management systems, smart glazing, innovative materials, and renewable solutions like photovoltaic panels. In this way, some components contribute mainly to energy performance, while others improve user comfort or strengthen the intelligence and adaptability of the building to environmental changes.

Building on this foundation, this chapter presents case studies. In these studies, climate remains constant, while building functions vary. This allows a comparative evaluation of theoretical expectations against realized skin applications, highlighting the strengths and weaknesses of each case.

4.1 Selection Criteria

The case studies in this thesis were selected based on the research objectives and the Quality Environmental Modules (QEM) framework, using an approach that controls climate as a constant variable. For this reason, projects located within Europe’s temperate oceanic climate zone were chosen. This ensures that differences in performance are not caused by environmental factors but instead reflect the design and operational strategies of the buildings. By keeping the climate constant, building function becomes the main factor of variation, making it easier to observe how different programmatic uses affect the design and performance of intelligent building skins.

Another important criterion was the presence of technologies related to intelligent building skins. The selected projects were required to include one or more of the following: dynamic or adaptive shading devices, smart glazing, photovoltaic (PV) panels or other on-skin renewable energy systems, sensor-based monitoring, IoT/BMS-based automation, adaptive or bio-reactive materials such as microalgae systems, and data-driven control methods such as closed-loop or machine learning systems. In addition, the availability of architectural documentation, technical descriptions, and performance data was essential to allow for an evidence-based evaluation within the QEM framework. This ensured that the projects could be analysed not only conceptually but also through measurable and realistic performance criteria.

To ensure recency and comparability, additional limitations were applied. First, only projects completed in 2010 or later were included, guaranteeing that the technologies studied represent current practices and innovations. Second, only medium-scale buildings between two and fifteen floors were considered. Very small single-story structures and very tall skyscrapers were excluded to maintain a balanced comparison in terms of scale. Finally, a minimum level of intelligent system integration was required, meaning that at least sensors and automated control mechanisms had to be present. This prevented the study from focusing on purely passive envelopes and kept the analysis centred on truly intelligent building skins.

After applying these criteria, four projects were selected to ensure both functional diversity and methodological consistency: The Edge (Amsterdam) an office building with fully integrated IoT/BMS systems and a PV-supported building skin, BIQ House (Hamburg) a residential building featuring a bio-reactive skin with a closed-loop control system and on-site energy management centre, FlectoLine Building Skin (Freiburg, 2024) an experimental adaptive building skin with machine learning-based control and integrated BIPV panels, and Cube Berlin (Berlin) a highly digitalized office building with an AI-driven management system, advanced user interaction through intelligent interfaces, and a fully glazed double-skin façade designed for energy efficiency and environmental responsiveness.

Together, these four case studies form a strong foundation for comparing how the QEM criteria of human comfort, energy efficiency, cost, environmental conditions, sustainability, safety, durability/maintainability, and intelligence/adaptability are addressed under consistent climate conditions but across different building functions.

4.2 Analysis and Results

The analysis in this chapter was conducted using the Quality Environmental Modules (QEM) framework to evaluate the performance of intelligent building skins. A comparative case study method was applied, with climate held constant to focus on differences caused by building function, technological integration, and design strategy.

The process began with a systematic examination of each case study, presented through a series of structured tables that aligned with the organization of Chapter 3. Each table summarized the main elements, while the accompanying text explained their roles and contributions in detail.

For each building, the analysis first provided general information, including location, year of construction, scale, function, and key characteristics, to establish context. Next, the intelligent systems integrated into the building were identified, covering control mechanisms, sensors, and the level of IoT/BMS integration. The analysis then focused on environmental and energy strategies, evaluating passive and active design approaches, renewable energy integration, and overall energy performance. Finally, the materials and building skin features were examined, with particular attention to glazing strategies, smart materials, and technologies specific to the skin design.

Once each case was analysed individually, the results were brought together in comparison tables, allowing for direct evaluation across shared QEM criteria such as human comfort, energy efficiency, sustainability, safety, durability, and adaptability. This comparative process revealed how different building functions and technologies influence the design and performance of intelligent building skins.

In the final stage, the findings were interpreted through a discussion of strengths and weaknesses for each project, providing insights into how intelligent skin strategies can be applied under consistent climatic conditions while addressing diverse functional and technological needs.

4.3 Selected Case One: The Edge

Location: Amsterdam, Netherlands

Year of Construction: 2014

Architect: PLP Architecture

Function: Office

The Edge is a 15-story, 40,000 square meter office building located in the Zuidas business district of Amsterdam, the Netherlands. Designed to bring together around 2,300 employees under one roof, the building includes not only office spaces but also facilities like a restaurant, cafe, meeting and reception areas, and a small convenience store. A defining feature of the building is its 58-meter-high atrium, which gives the space a distinctive character. Oriented to the north, the atrium allows generous daylight to flood the interior even on cloudy days while also providing a sense of openness and visual comfort for occupants. Beyond its aesthetic role, the atrium also contributes functionally by acting as part of the building’s natural ventilation system, helping to remove stale air from the upper zones of the offices (Coleman et al., 2019). In addition, the basement provides parking for 500 bicycles as well as electric-vehicle charging units, encouraging low-carbon commuting (Jalia et al., 2019).

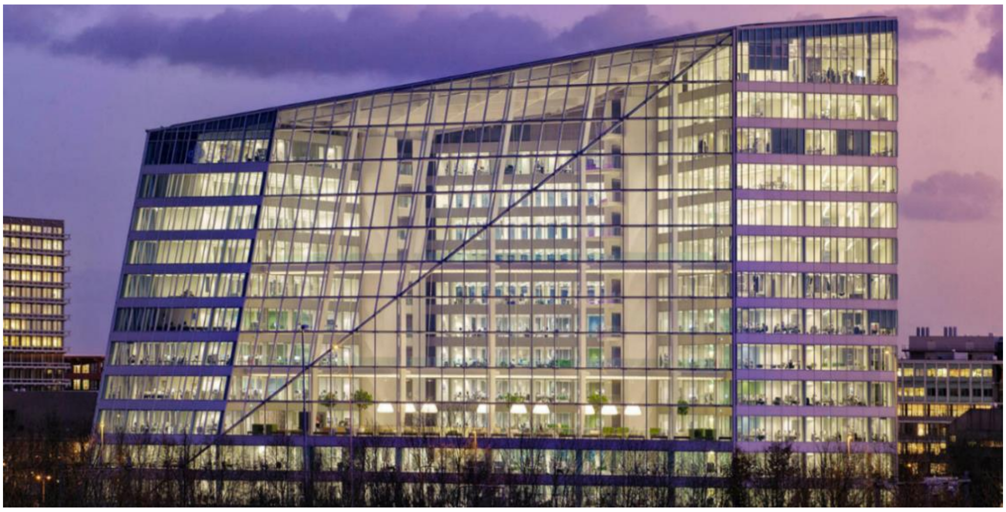


Figure 23: North-Facing Atrium at Night (PLP Architecture, n.d.).

Recognized by BREEAM in 2019 as the world's intelligent and most sustainable building, The Edge integrates advanced technologies that reduce carbon emissions and operational costs, while prioritizing user comfort and efficiency. Aiming for net-zero energy use, it achieved an exceptional BREEAM-NL rating of 98.36% the highest score ever recorded making it a benchmark in sustainable and intelligent building design (Coleman et al., 2019).

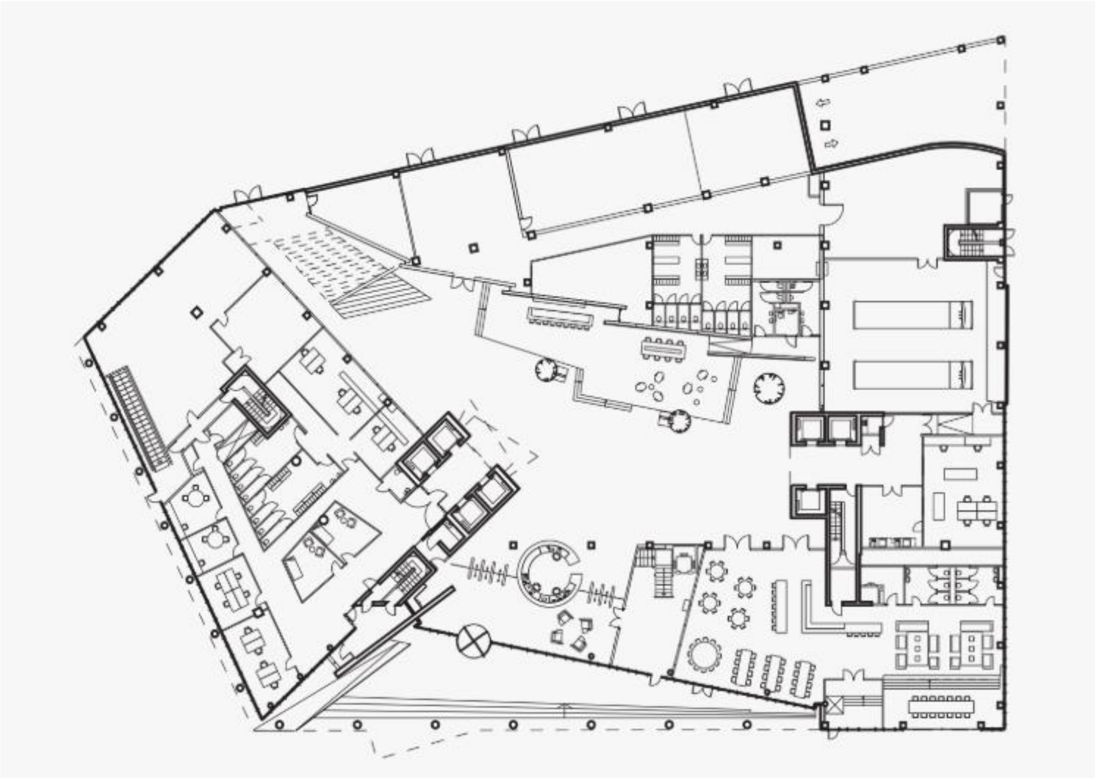


Figure 24: Ground Floor Plan (PLP Architecture, n.d.).

The Edge's design approach aims to maximize user experience and social interaction. In this context, the building stands out with its architectural layout and integrated intelligent systems. The architectural concept of The Edge is organized around a "social condenser" that forms the core of the building. This central atrium, connected by bridges and exposed elevator shafts, creates hubs for both vertical and horizontal interaction, fostering planned as well as spontaneous collaboration. At the same time, the atrium acts as a transparent interface with the city projecting the building's internal activities outward while framing views of its surroundings for those inside (Edge, n.d.).

Used air is directed from the rooms into the atrium and then transferred to the central air-handling unit (AHU) on the roof. This system creates an efficient return-air cycle between the atrium and the AHU.

On the south side, heavy load-bearing walls absorb heat during the day, providing thermal mass that helps to stabilize indoor temperatures (Jalia et al., 2019). Extending to the roof, the low-emissivity glass façade enhances daylight penetration while minimizing heat gain, thereby supporting both visual comfort and energy efficiency.

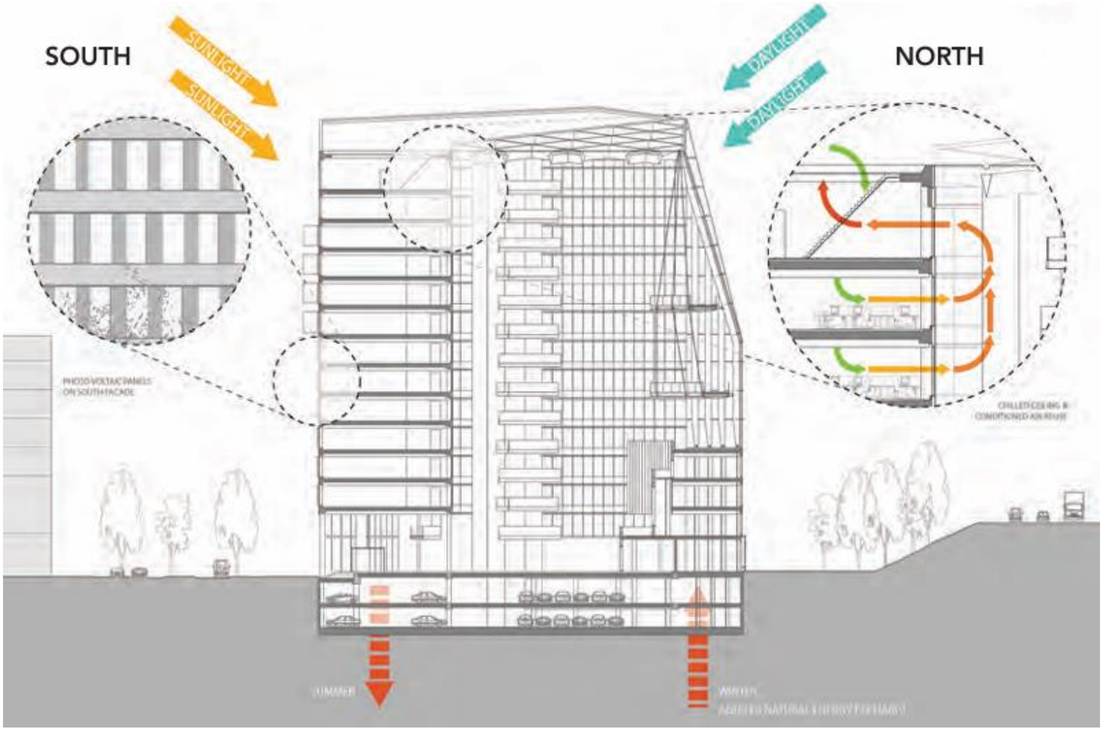


Figure 25: Section (PLP Architecture, n.d.).

Rather than fixed desk arrangements, The Edge operates on an "activity-based working" model, offering a wide variety of environments such as focus rooms, work booths, balcony desks, and open collaboration zones. This flexible setup is supported by a mobile application that enables users to personalize lighting and temperature settings, locate colleagues, and identify available workstations (Edge, n.d.). The Mapiq app presents a navigable 3D floor model, lets employees see where colleagues have checked in, and remembers each user's preferred lighting and thermal comfort settings. Meeting-room lights flicker 15 minutes before a booking ends as a gentle nudge. Deloitte standardized devices by providing iPhones, and the app was optimized for this platform (Jalia et al., 2019). Through this integration of architecture and smart technology, the building delivers a highly adaptable, efficient, and user-centered working environment (Edge, n.d.).

Figure 26: Mapiq's Customised App for Deloitte Guides Users to Their Destinations with A 3-D Model of The Edge (Jalia et al., 2019).

In terms of technical systems, The Edge uses an advanced thermal energy storage system connected to an aquifer located 130 meters underground. Two separate boreholes store water at different temperatures (6°C for cooling and 18°C for heating), supported by a high-efficiency heat pump to optimize performance. The heating and cooling are distributed through water-filled pipes integrated beneath each floor slab. This seasonal storage method works like an 'earth battery,' keeping heat in the summer and using it again in the winter to make the system more efficient (Jalia et al., 2019).

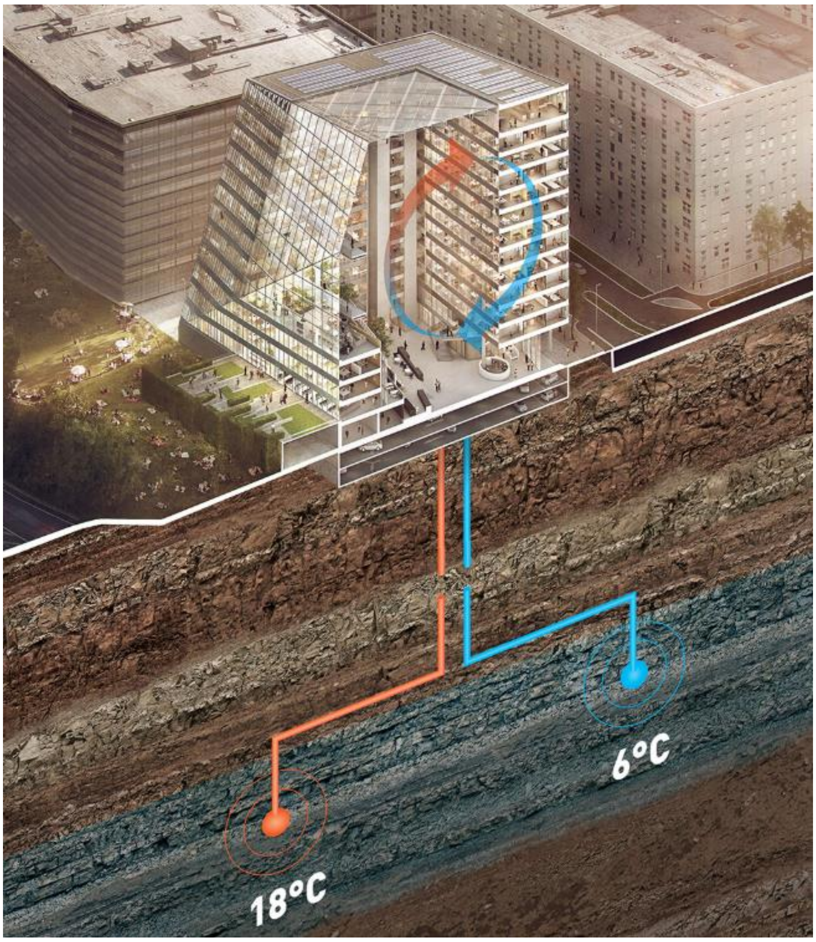


Figure 27: The Aquifer Thermal Energy Storage System (PLP Architecture, n.d.).

The building also features a Philips-developed Ethernet-powered LED lighting system with 6,000 luminaires, some equipped with sensors for heat, movement, and light levels. This smart lighting network allows individual control of illumination via a central system, reducing lighting energy use by approximately 50% (Kara, 2017). At The Edge, Philips developed a new PoE LED panel where each light has its own IP address for remote control and adjustment. The product later entered Philips' standard catalogue and supports additional sensors through an open, extensible architecture. To achieve net-zero, photovoltaic generation is distributed across the campus: approximately 1,920 m² installed on The Edge itself and a further ~2,280 m² on rented neighbouring rooftops, extending production beyond the primary site. Rainwater is collected through roof and façade drainage systems and reused for landscape irrigation, green roof gardens above the atrium, and toilet flushing. Landscape irrigation is a notable reuse stream in addition to toilet flushing (Jalia et al., 2019). Building skin design varies by orientation: the north skin, facing the atrium and highway, is transparent to maximize daylight while using thick glazing to reduce noise pollution; the south skin integrates photovoltaic panels for both energy generation and solar shading; the east and west skin incorporate closely spaced elements and operable windows to allow for natural ventilation and glare control. Additionally, skin air vents are oriented according to the sun's path to prevent heat buildup (Kara, 2017).

Figure 28: Solar Pv Panels on The South Side and Atrium (PLP Architecture, n.d.).

Over the first decade, the integrated measures implemented at The Edge are estimated to have prevented approximately 42 million kg of CO_2 emissions. On the operations side, floor-level computers connected to zone controllers enable localized control and faster fault detection. The Vecos smart locker system works in integration with Mapiq, providing reservations, inactivity alerts, and self-service password resets; as a result, the routine workload of CBRE’s facilities team is reduced.

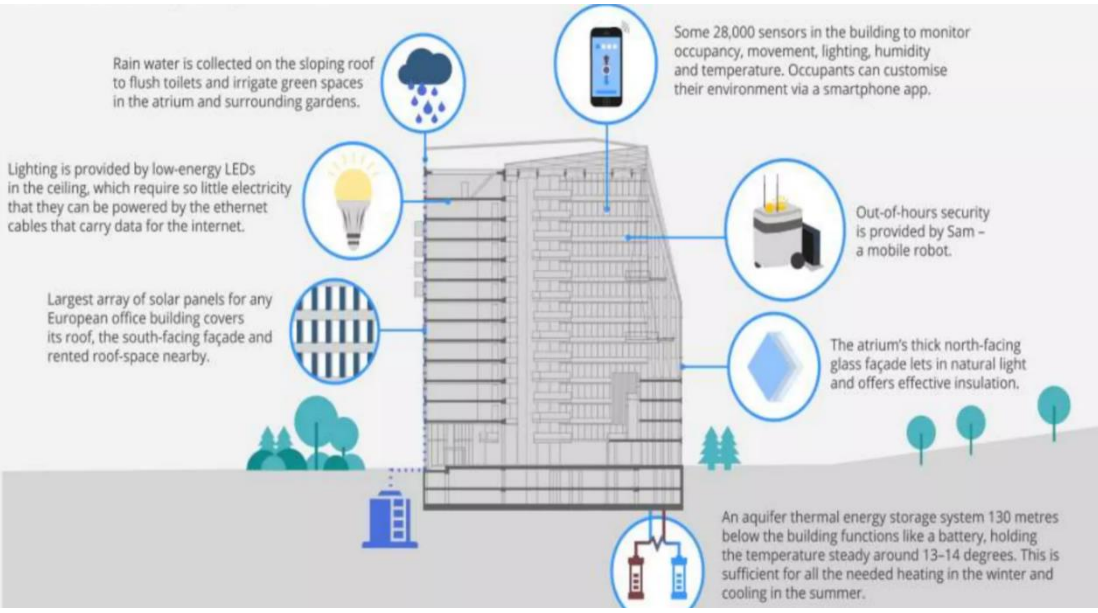


Figure 29: Selected Features of The Edge Building (Ahmed, n.d.).

Data management is handled through purpose-specific channels: Mapiq supplies office-occupancy dashboards, while Schneider Electric BMS data is visualized with Microsoft Power BI. Given the accessibility and capability of these tools, a single unified dashboard was not considered necessary. Project specifications were prepared to be future-proof, supporting predictive maintenance and expanded occupancy analytics, and data processing follows GDPR-compliant governance. During construction, an optimized mix of prefabricated components was assembled on site, which shortened the schedule and reduced logistics-related impacts (Jalia et al., 2019).

Figure 30: Efficient Construction of The Edge Comprised Prefabricated Building Assembled at Site (Jalia et al., 2019).

4.3.1 Results of Case Study One

In this section, the case study of The Edge is analysed through a series of tables developed to systematically evaluate the building's skin and intelligent systems. These tables are directly aligned with the structure of Chapter 3, ensuring that each system category is examined consistently across all case studies.

The analysis begins with an overview of the building, followed by the identification of intelligent building systems. It then continues with an assessment of environmental control and energy strategies and concludes with the examination of the materials and glazing technologies used in the building skin. Each table presents the key components in a clear and concise format, while the accompanying text provides detailed explanations of their roles, functions, and contributions.

This structured approach allows The Edge to be evaluated in a clear and comparable way, establishing a solid foundation for the subsequent case studies and the comparative analysis presented later in this chapter.

Table 2: General Information of The Edge (Author, 2025).

Category	Details
Location	Amsterdam, Netherlands
Year of Construction	2014
Architect	PLP Architecture
Function	Office (Deloitte HQ)

Climate Zone	Temperate Oceanic
Height / Floors	15 floors / 58 m atrium
Construction Area	40,000 m²
Structural System	Steel-reinforced concrete
Building Skin Type	Single skin facade

Table 2 provides an overview of the key characteristics of The Edge, outlining its location, design team, structural system, and basic building features. These general details form the foundation for understanding the building's context and the strategies used in its design. This information is essential for interpreting the intelligent systems and façade solutions analysed in the following sections.

Table 3: Intelligent Building Systems of The Edge (Author, 2025).

Systems	Technologies Implemented at The Edge
Control System	Closed-loop (extrinsic) control
Sensors	Light, thermal, and motion sensors (integrated in PoE LED fixtures); user presence/check-in data (Mapiq system)
IoT (Internet of Things)	PoE-based IP-addressable LED network (6,000 fixtures); Mapiq mobile app and 3D floor plan; Vecos smart locker integration; floor-level zone controllers and fault detection; data visualization (Mapiq dashboard, Schneider BMS → Power BI)
BMS (Building Management System)	Schneider Electric BMS; centralized management of HVAC, lighting, and operational systems; predictive maintenance support; GDPR-compliant data governance

Table 3 summarizes the intelligent building systems implemented at The Edge. The Edge operates with an integrated intelligent system that connects its building skin and internal building services. The closed-loop control system continuously collects data through a network of light, thermal, and motion sensors embedded in PoE LED fixtures, as well as user check-in data from the Mapiq platform. This real-time information is transmitted to the Building Management System (BMS), which processes the data and sends automated commands to lighting fixtures, and HVAC components. The IoT infrastructure, consisting of IP-addressable LED luminaires, the Mapiq mobile application, and smart lockers by Vecos, creates a connected digital ecosystem. Floor-level zone controllers enable localized management and quick fault detection, while dashboards from Mapiq and Schneider Electric provide clear visualization of operational data through Power BI. The BMS oversees all core building functions, including lighting, HVAC, security, and energy performance, ensuring predictive maintenance and GDPR-compliant data governance. Together, these technologies make The Edge a highly adaptive, energy-efficient, and user-centred intelligent building.

Table 4: Environmental Control & Energy Systems of The Edge (Author, 2025).

System Category	Technologies at The Edge
Solar Collector & PV Panels	1,920 m² PV on The Edge roof, 2,280 m² PV on neighbouring roofs, south skin PV panels
Solar Control Systems	South skin PV panels, east/west skin with dense elements and operable windows

Table 4 outlines the environmental control and energy strategies integrated into the building skin of The Edge. The Edge integrates renewable energy and solar control strategies into its façade design. A total of 1,920 m² of photovoltaic panels are installed on The Edge roof, with an additional 2,280 m² placed on neighbouring rented rooftops.

These PV panels on the south façade serve a dual purpose by generating electricity and providing shading to reduce heat gain. For solar control, the south façade relies on PV panels as shading elements, while the east and west façades feature closely spaced elements and operable windows. This configuration enhances natural ventilation and reduces glare, contributing to both energy efficiency and occupant comfort.

Table 5: Materials and Glass Systems of The Edge (Author, 2025).

System Category	Technologies at The Edge
Energy-Efficient Glazing	Low-emissivity glass on all façades, thicker glazing on the north façade for noise control
Smart Glass	Not used
Smart Materials	Photovoltaic panels integrated into the south façade, functioning as energy-generating and shading elements

Table 5 presents the material and glazing strategies applied to The Edge façade, providing a foundation for the detailed discussion that follows. The Edge utilizes low-emissivity glazing throughout its building skin design to enhance natural daylight while minimizing heat gain. On the north side, thicker glazing is applied to reduce noise from the nearby highway while maintaining transparency and visual comfort. No smart glass technologies are implemented in The Edge. Instead, the building integrates smart materials in the form of photovoltaic panels. These panels are embedded into the south façade and serve a dual function: generating renewable energy and acting as shading elements. This combination of glazing and material strategies improves energy performance, visual comfort, and overall building skin efficiency.

The Edge demonstrates how an integrated approach to intelligent building systems, environmental control strategies, and advanced materials can create a highly adaptive and efficient building skin. Through the use of IoT-enabled control systems, the building continuously monitors and responds to external conditions and user needs, ensuring real-time optimization of lighting, HVAC, and shading operations. The integration of photovoltaic panels into the south side highlights the dual role of energy generation and passive solar control, while the east and west side enhance natural ventilation and reduce glare through their dense structural design and operable windows.

The combination of low-emissivity glazing and smart material applications contributes to visual comfort, noise reduction, and energy performance. With a total of 4,200 m^2 of photovoltaic surface area, The Edge achieves substantial renewable energy production, supporting its goal of net-zero operation and reducing CO_2 emissions by approximately 42 million kg over the first decade.

These findings position The Edge as a benchmark for sustainable intelligent building skin design.

4.4 Selected Case Two: BIQ House

Location: Hamburg, Germany

Year of Construction: 2013

Architect: Splitterwerk Architects (in collaboration with Arup)

Function: Residential (Pilot Project)

A pilot project, BIQ House (Bio Intelligent Quotient), features the world's first bioreactive skin design (Arup, n.d.). The BIQ House is a four-story cubic structure made of stone and concrete, with a penthouse level that together contain 15 apartments. While the ground floor hosts technical and public service spaces, the upper floors include residential units, among which the duplex and a few others follow an experimental interior design approach.

Figure 31: BIQ House (Arup, n.d.).

In these apartments, rooms are not given fixed functions. Instead, they are designed as neutral, reconfigurable spaces supported by built-in furniture that allows different uses to be activated or hidden as needed. This flexibility enables a single space to take on multiple roles depending on the occupants' requirements. Even windows can be covered with internal shutters or sliding partitions, reinforcing the adaptability of the layout. This design philosophy reflects contemporary housing demands and draws inspiration from modernist precedents such as Mies van der Rohe's flowing spaces, Frank Lloyd Wright's open layouts, Adolf Loos's spatial concepts, and the efficiency of the Frankfurt kitchen. The result is a housing model that is permanently reconfigurable, responsive to the changing needs of its users (IBA Hamburg, 2013). The bio-reactive façade system known as SolarLeaf produces renewable energy by using biomass from algae and solar thermal energy. The BIQ building in Hamburg, Germany, is equipped with 200 square meters of algae-filled panels, which not only meet the energy needs of the building but also help reduce CO_2

emissions by around 6 tons per year**.** The glass bioreactors placed on the south-facing façades create a suitable environment for photosynthesis**.** At the same time, the system provides additional benefits such as shading, thermal insulation, and noise reduction**.** With this technology, the BIQ house can generate energy in a carbon-neutral way and also acts as a carbon sink by using algae to absorb CO_2 from the atmosphere (FEEM, n.d.).

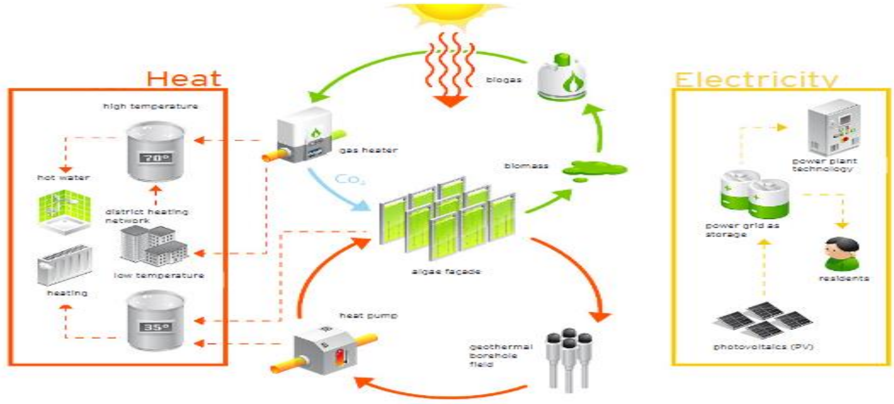


Figure 32: BIQ Energy Centre Chart (IBA Hamburg, 2013).

The bioreactors also function like solar thermal collectors, reaching temperatures of up to 35 °C. The captured heat is transferred to the building's energy centre, where it is used for space heating and domestic hot water, with surplus stored in geothermal boreholes. The harvested biomass is filtered, converted into biogas, and fed into the city's energy network. At the same time, the CHP provides the CO_2 needed for the façade, while its waste heat is reused in the district heating system (IBA Hamburg, 2013).

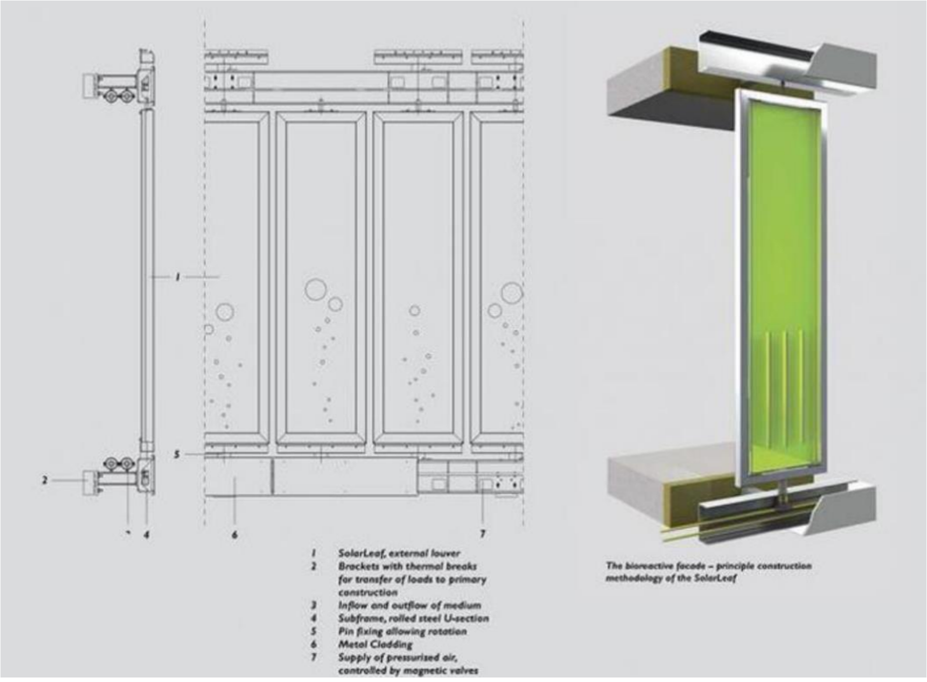


Figure 33: Section Detail of The Solarleaf Bioreactive Façade Panels Used in The BIQ House (Poverty Pollution Persecution, 2021).

Microalgae are cultivated inside flat-panel photobioreactors (PBRs) integrated into the building skin, requiring no additional land use and being only minimally affected by weather conditions. Each bioreactor consists of four layers of glass: the two inner panes create a 24-liter cavity for the culture medium, while argon-filled cavities on either side reduce heat loss. Compressed air is periodically introduced to create turbulence, which enhances CO_2 absorption and light capture, while also cleaning the internal surfaces with a water-air-plastic scrubber mixture (Arup, n.d.).

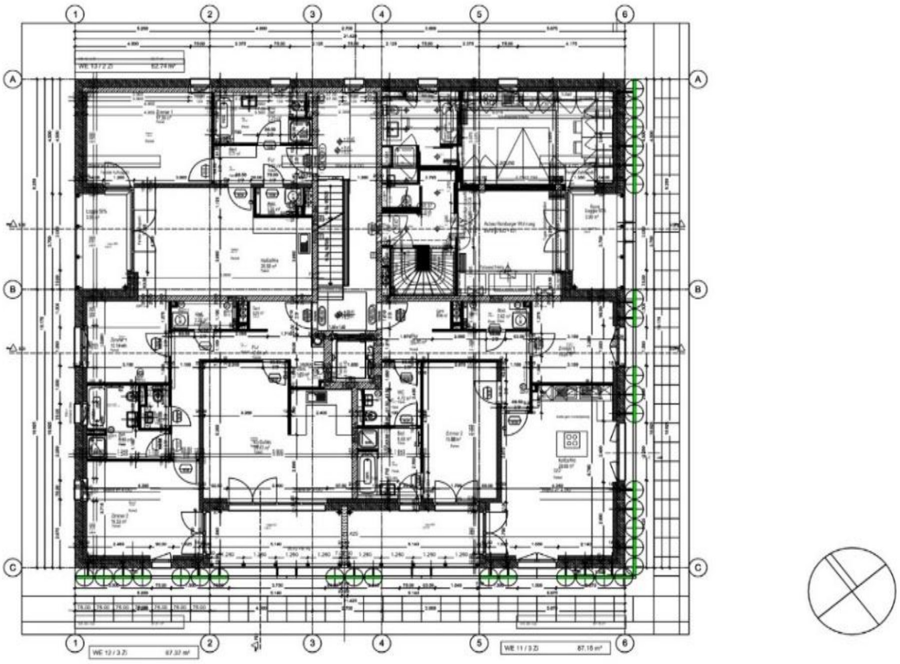


Figure 34: Plan of BIQ House (Ongreening, n.d.).

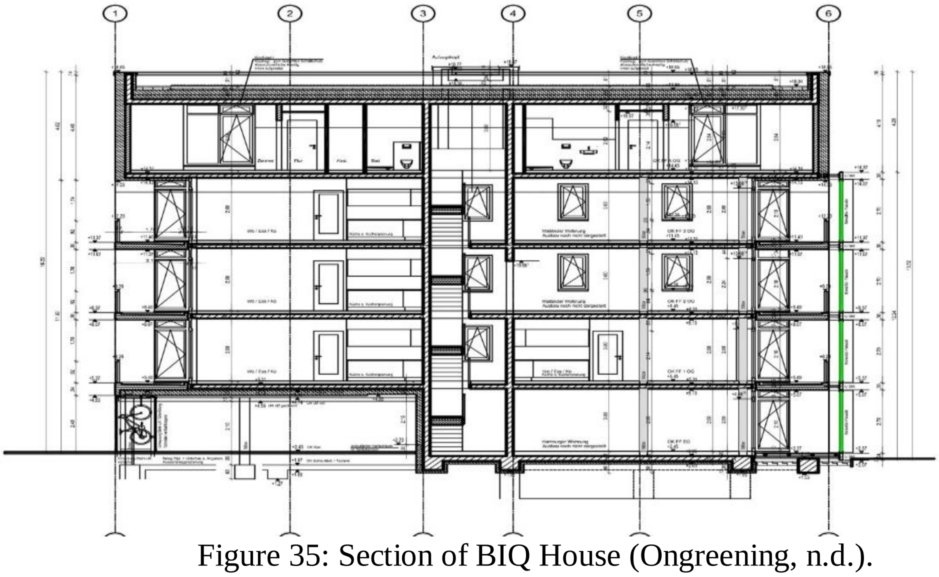


Figure 35: Section of BIQ House (Ongreening, n.d.).

Microalgae are cultivated inside flat-panel photobioreactors (PBRs) integrated into the building skin, requiring no additional land use and being only minimally affected by weather conditions. Each bioreactor consists of four layers of glass: the two inner panes create a 24-liter cavity for the culture medium, while argon-filled cavities on either side reduce heat loss. Compressed air is periodically introduced to create turbulence, which enhances CO_2 absorption and light capture, while also cleaning the internal surfaces with a water-air-plastic scrubber mixture. A total of 129 bioreactors, each measuring 2.5 m x 0.7 m, are installed on the southwest and southeast side of building, functioning as a secondary building skin system. These panels supply roughly one-third of the total thermal energy demand for the building's 15 residential units (Arup, n.d.).

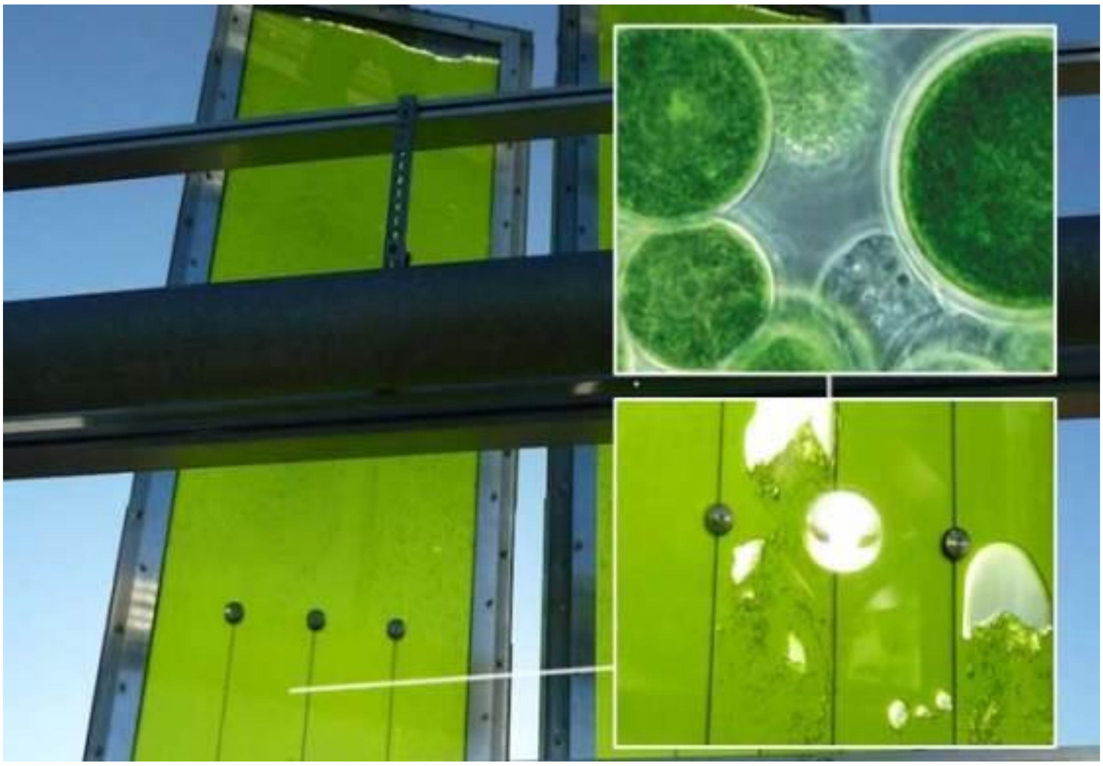


Figure 36: Microalgae-Filled Photobioreactor Panel Providing Dynamic Shading and Energy (Beciri, 2013).

The BIQ's holistic energy concept combines solar thermal energy, geothermal storage via 80-meter-deep brine-filled borehole heat exchangers, and biomass conversion in external biogas plants. Excess heat is stored seasonally and used according to demand for example, for heating in winter or for alternative industrial applications such as cosmetics and food production during the summer months when algae growth is at its peak The panels' distinctive green colour makes the process of photosynthesis and CO_2 absorption visible from the outside, intentionally contributing to the architectural expression of the building (IBA Hamburg, 2013). As a result, BIQ House is equipped with a bioreactive building skin system that generates renewable energy using algae while also providing shading, thermal insulation, and noise reduction. This system operates through a closed-loop control mechanism, automatically regulating algae cultivation and energy flow based on real-time data (IBA Hamburg, 2013). Inside the algae panels, sensors monitor critical parameters such as CO_2 concentration, temperature, light intensity, and water quality. This information helps maintain optimal conditions for algae growth and supports efficient energy production (Arup, n.d.). BIQ House does not feature an IoT network. Instead, all data is collected and managed within the Energy Management Centre, which also oversees thermal storage and biomass conversion processes (IBA Hamburg, 2013).

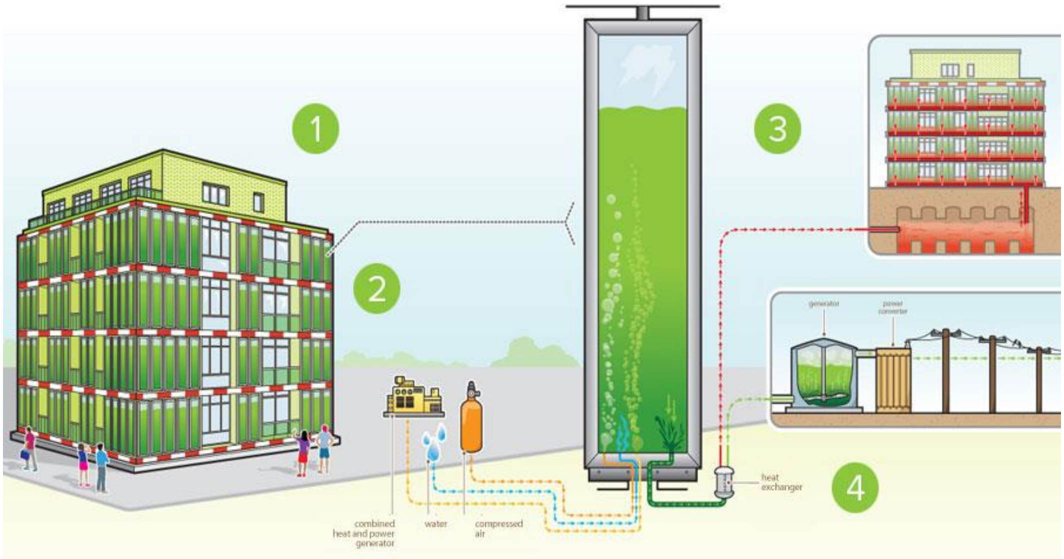


Figure 37: BIQ House Algae Façade System (Ferris, 2013).

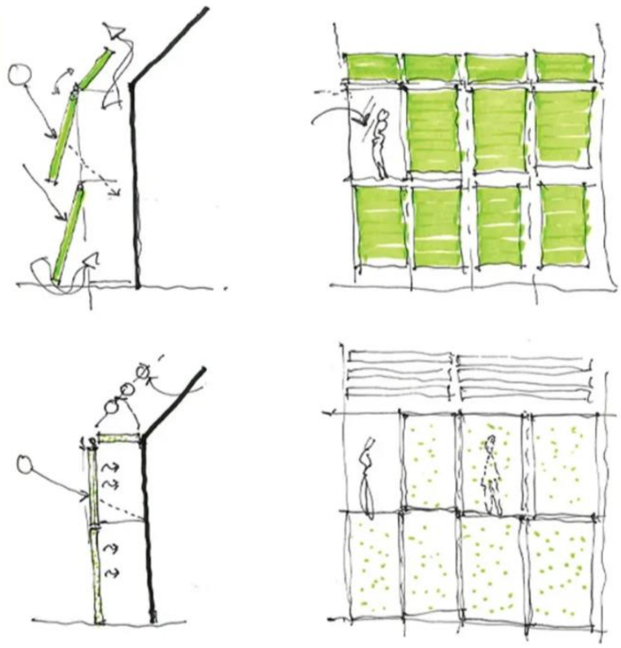


Figure 38: Cultivating Microalgae in Flat-Panel Pbrs Does Not Require Additional Site Area and Is Largely Unaffected by Weather Conditions (Arup, n.d.).

4.4.1 Results of Case Study Two

In this section, the case study of BIQ House is examined through a series of tables that systematically assess the building skin and intelligent systems. While following the same structure as Chapter 3 for consistency across all case studies, the analysis highlights the unique characteristics of BIQ House, particularly its bioreactive building skin technology.

The evaluation begins with general information about the building and continues with an overview of the intelligent systems integrated into its design. It then addresses the environmental control and energy strategies employed in the building skin, before concluding with an analysis of the materials and glazing technologies. Each table presents key information in a clear and concise format, while the accompanying text explains the functions and contributions of these elements in greater detail.

This approach provides a comprehensive understanding of BIQ House and sets the stage for its comparison with other case studies in the later parts of this chapter.

Table 6: General Information of BIQ House (Author, 2025).

Category	Details
Location	Hamburg, Germany
Year of Construction	2013
Architect	Splitterwerk Architects (in collaboration with Arup)
Function	Residential (Pilot Project)
Climate Zone	Temperate Oceanic
Height / Floors	5 floors (including penthouse)
Construction Area	1,600 m²
Structural System	Stone and reinforced concrete
Building Skin Type	Double-skin façade with bioreactive SolarLeaf panels

Table 6 provides an overview of the key characteristics of BIQ House, including its location, design team, structural system, and main building features. These general details establish the context of the project and give insight into the innovative building skin strategies implemented. This background information is essential for understanding the building’s bioreactive double-skin system and its integration with intelligent design principles discussed in the following sections.

Table 7: Intelligent Building Systems of BIQ House (Author, 2025).

System Category	Technologies Implemented at BIQ House
Control System	Closed-loop system
Sensors	Located inside algae panels; monitor CO_2 levels, temperature, light intensity, and water quality to optimize algae growth and system performance
IoT (Internet of Things)	Not implemented
BMS (Building Management System)	Limited system: Energy Management Centre

Table 7 summarizes the intelligent building systems of BIQ House, focusing on the building's unique bioreactive building skin technology. The building uses a closed-loop control system to manage both algae cultivation and thermal energy flow. This automated system continuously collects and processes data to ensure the system operates at maximum efficiency. Sensors are embedded directly inside the algae panels and measure key parameters such as CO_2 levels, temperature, light intensity, and water quality. This information is essential for regulating algae growth, improving photosynthesis efficiency, and maximizing energy production.

Unlike fully digitized smart buildings such as The Edge, BIQ House does not include an IoT network. All monitoring and control activities are carried out locally within the Energy Management Centre, meaning the data is not connected to cloud services or external networks. This centre functions as a limited Building Management System (BMS), focusing only on managing the algae panels and thermal storage processes, rather than providing full control over all building systems.

Table 8: Environmental Control & Energy Systems of BIQ House (Author, 2025).

System Category	Technologies Implemented at BIQ House
Solar Collector & Photovoltaic Panels	129 algae panels on southwest and southeast of building skin; generate heat for space heating and hot water; excess heat stored in geothermal boreholes; biomass converted to biogas for city network
Solar Control Systems	Algae panels provide shading, thermal insulation, and noise reduction on south building skin

Table 8 outlines the environmental control and energy strategies integrated into BIQ House. The building's SolarLeaf building skin system features 129 algae-filled panels installed on the southwest and southeast side of building. These panels act as bioreactors, where algae grow through photosynthesis, absorbing CO_2 and releasing oxygen. The thermal energy generated inside the panels can reach up to 35°C, providing heat for space heating and domestic hot water. Any excess heat is stored in 80-meter-deep geothermal boreholes for seasonal use. The harvested biomass is converted into biogas, which is then fed into the city's energy network. Additionally, a combined heat and power (CHP) system supplies the CO_2 required for algae cultivation and recycles its waste heat for the district heating system (IBA Hamburg, 2013; Arup, n.d.). Beyond energy production, the algae panels contribute to solar control by acting as natural shading devices. They also improve thermal insulation and reduce noise transmission, supporting both energy efficiency and occupant comfort.

Table 9: Materials and Glass Systems of BIQ House (Author, 2025).

System Category	Technologies at BIQ House
Energy-Efficient Glazing	Four-layer glass; inner layers form 24-liter cavity for algae culture; outer argon-filled layers reduce heat loss
Smart Glass	Not used
Smart Materials	SolarLeaf bioreactive algae panels as a secondary building skin; produce energy, absorb CO_2, and create a visible green architectural expression

Table 9 presents the materials and glazing strategies applied to the BIQ House building skin. The algae panels consist of a four-layer glass system. The inner layers create a 24-liter cavity for the algae culture medium, while the outer argon-filled layers help minimize heat loss. No smart glass technologies are used in BIQ House. Instead, the project integrates smart materials in the form of SolarLeaf panels. These panels serve as a secondary building skin system, generating energy, absorbing CO_2, and making the process of photosynthesis visually accessible to the public. This approach merges material innovation with sustainability and architectural expression.

In summary, BIQ House shows how intelligent building skin technologies can combine biological processes with architectural design to create a sustainable and adaptable building system. Its SolarLeaf bioreactive building skin functions as a closed-loop system, where algae cultivation, energy production, and thermal management are continuously regulated by sensors and automated controls. This integration transforms the building skin from a passive building skin into an active component that not only provides shading, insulation, and noise reduction but also generates energy. While BIQ House does not include a full IoT network or comprehensive BMS, its localized Energy Management Centre effectively manages the operation of the algae panels and thermal storage. This makes the building an early and significant example of intelligent building skin strategies focused on renewable energy generation and environmental performance. BIQ House also demonstrates the potential of smart materials to redefine the role of the building skin.

4.5 Selected Case Three: FlectoLine Facade

Location: Freiburg, Germany

Year of Construction: 2024

Architect: University of Stuttgart-ITKE & ITFT (in collaboration with University of Freiburg & University of Tübingen)

Function: Botanical Garden Building

Developed as part of the international research project *Flectuation*, the FlectoLine façade system is an innovative responsive shading installation located at the Botanical Garden of the University of Freiburg. Using compliant mechanisms based on hingeless elastic deformation, the system avoids the mechanical complexity and geometric limits of traditional rigid façades. An advanced control setup records user and environmental responses, which are processed by machine learning to predict optimal actuation in different scenarios. Covering 83.5 m², FlectoLine represents a future-oriented approach to retrofitting existing buildings, allowing them to adapt to changing outdoor conditions and indoor use patterns. By integrating Building-Integrated Photovoltaics (BIPV), the system combines renewable energy generation with reduced energy consumption, offering a holistic building envelope solution.

Building on over a decade of research by the University of Stuttgart's ITKE and ITFT, FlectoLine is the first fully functional outdoor responsive façade prototype of its kind. As an evolution of earlier indoor demonstrators such as FlectoFold and FlectoSol, it unites sustainability with enhanced architectural performance in real-world application (University of Stuttgart, Institute of Building Structures and Structural Design, 2024).

Figure 39: Front View of Flectoline Façade with Semi-Closed Modules (University of Stuttgart, Institute of Building Structures and Structural Design, 2024).

The FlectoLine demonstrator was inspired by biomimetic research carried out in collaboration between the universities of Stuttgart, Freiburg, and Tübingen. Two biological role models guided the design. The first is the waterwheel plant (*Aldrovanda vesiculosa*), which generates motion through motor cells aligned along its central spine and driven by turgor pressure. This principle was adapted to the linear actuator zones of the FlectoLine modules. The second model is the wing structure of the insect *Graphosoma italicum*. Its folding motion is initiated by veins surrounded by a combination of stiff (sclerotin) and elastic (resilin) materials. Studies showed that flexible areas in the actuation zones reduce stress from internal pressure and that the direction of movement depends on the distribution of stiff material around the veins. As a result, the motion mechanism of FlectoLine directly follows the structural logic of biological systems (University of Stuttgart, Institute of Building Structures and Structural Design, 2024).

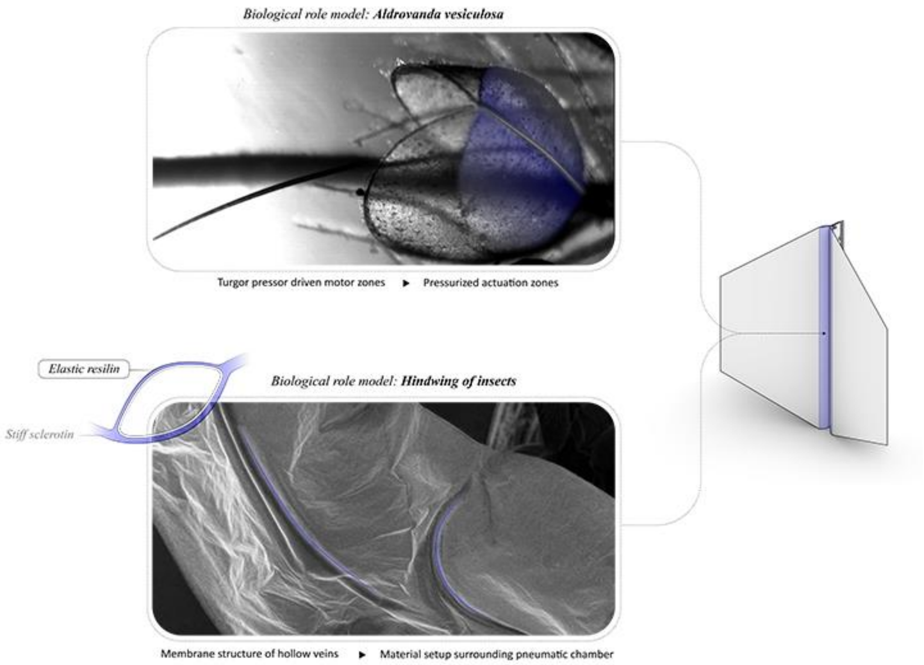


Figure 40: Biological Role Models for The Responsive Module´s Development (University of Stuttgart, Institute of Building Structures and Structural Design, 2024).

In addition, FlectoLine consists of fiber-reinforced composite plates with built-in hinge zones, designed to work with pneumatic actuators. The actuators, shaped like cushions, are directly integrated into the composite. The material structure is arranged so that the part beneath the actuator is stiffer, while the part above it is more flexible. When pressure is applied, the actuator deforms more strongly on the flexible side, causing the entire plate to bend in that direction. In this way, the folding motion occurs without the need for mechanical connections.

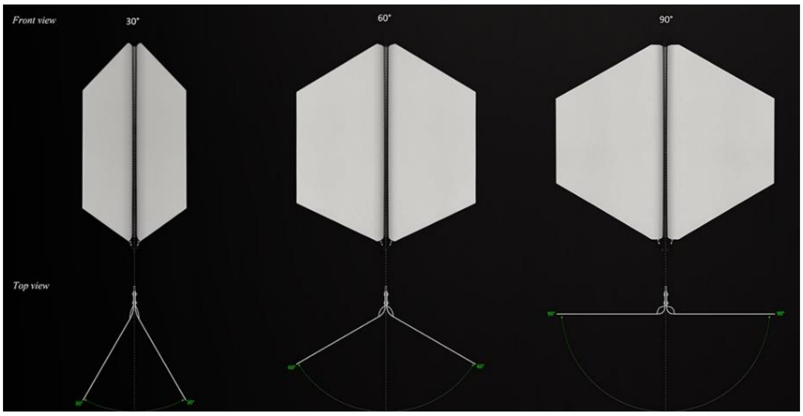


Figure 41: Flectoline-Module in Different Actuation Stages (University of Stuttgart, Institute of Building Structures and Structural Design, 2024).

Two different material systems were developed for the façade application. The first is a bio-inspired hybrid composite made of elastic and stiff layers, combining elastomer components with fiber-reinforced thermoset material. Similar to insect wing veins, the asymmetric distribution of stiff layers defines the direction of movement, and previous tests have already proven its reliability for large-scale use.

To make production faster and more cost-efficient, a second alternative system was created using thermoplastic materials. In this case, two polyamide-6 layers with different stiffness levels were joined together with an elastic strip.

Both systems were equipped with a protective outer layer to ensure durability under outdoor conditions. They were tested for fire resistance, weathering, and wind loads, and to guarantee long service life, each was subjected to up to 20,000 pneumatic actuation cycles with bending angles of up to 90.

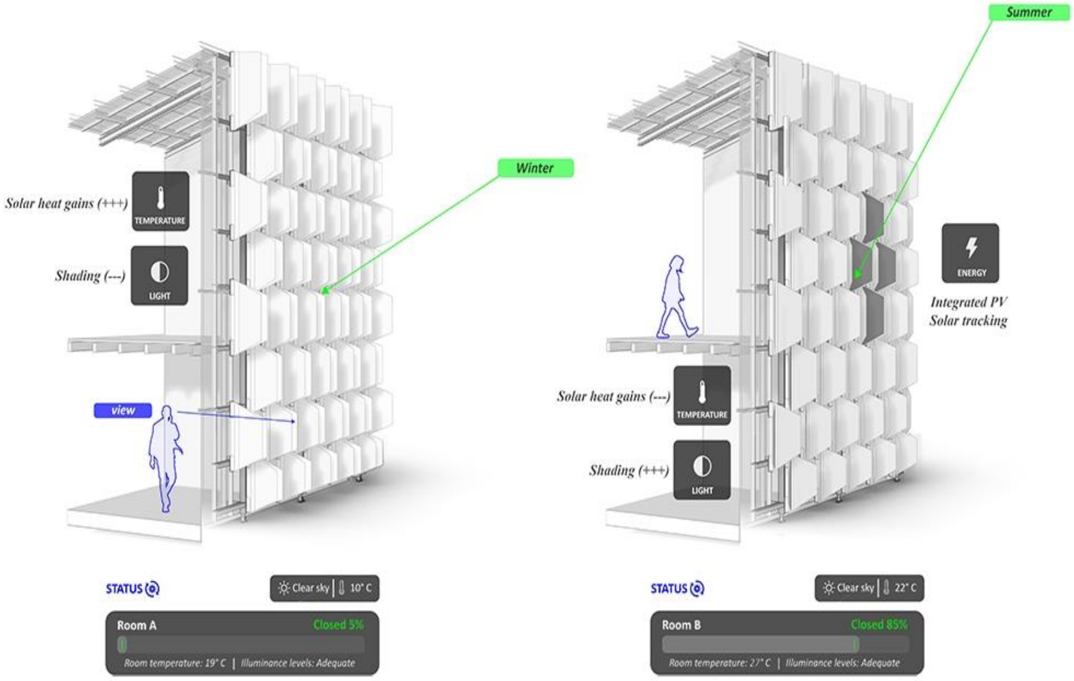


Figure 42: Axonometric Section of Façade in Two Seasons (University of Stuttgart, Institute of Building Structures and Structural Design, 2024).

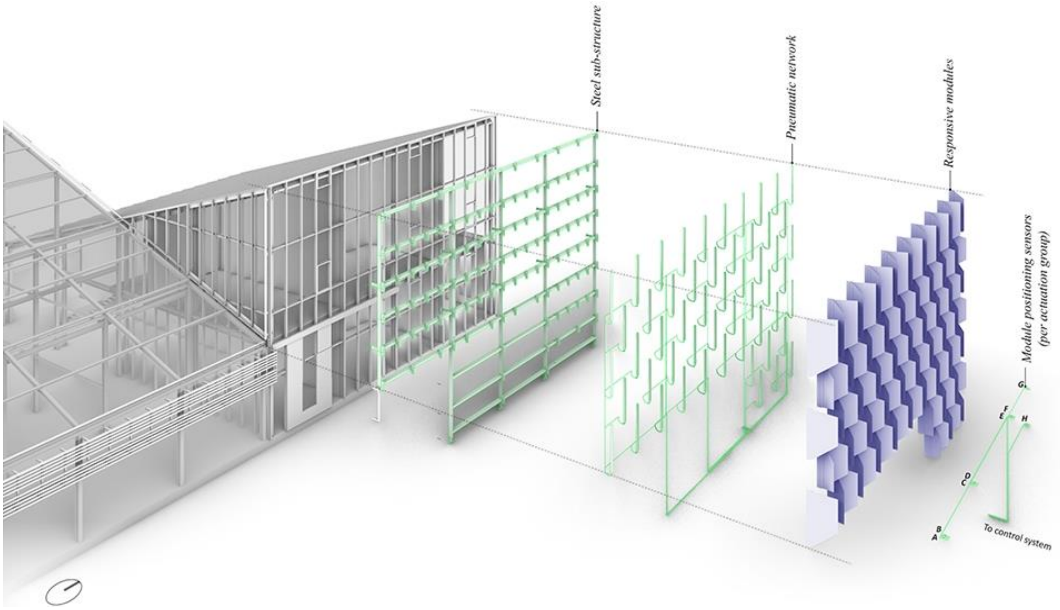


Figure 43: Exploded Façade Components (University of Stuttgart, Institute of Building Structures and Structural Design, 2024).

A digital twin was developed to manage the performance of the responsive façade by simulating the lighting, thermal behaviour, and energy generation of the integrated PV panels in real time. The system collects data from embedded sensors, such as indoor and outdoor light levels, temperature, and wind conditions, and combines them with weather forecasts and predicted energy demand. Using this information, a decision-tree algorithm adjusts the panel angles throughout the day to achieve the best balance between user comfort, energy efficiency, and renewable energy production. Comfort is optimized in three ways: maintaining brightness, reducing glare, and regulating indoor temperature (University of Stuttgart, Institute of Building Structures and Structural Design, 2024).

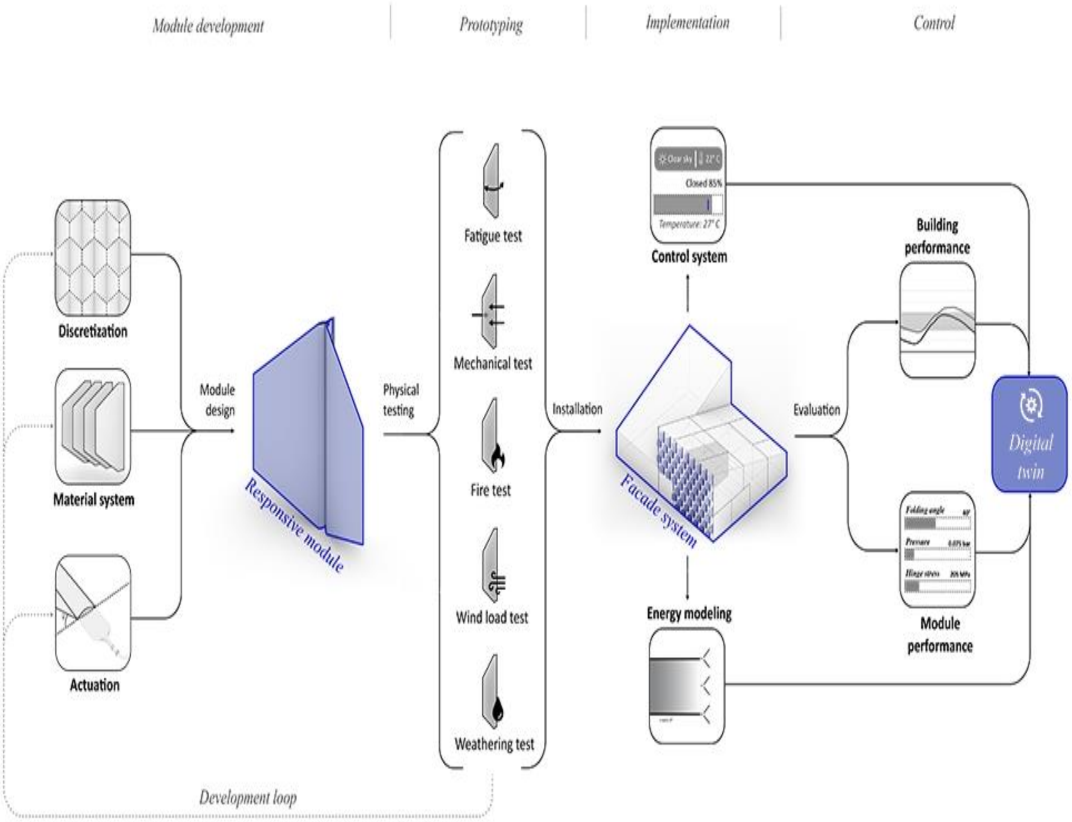


Figure 44: Flectoline Development Process (University of Stuttgart, Institute of Building Structures and Structural Design, 2024).

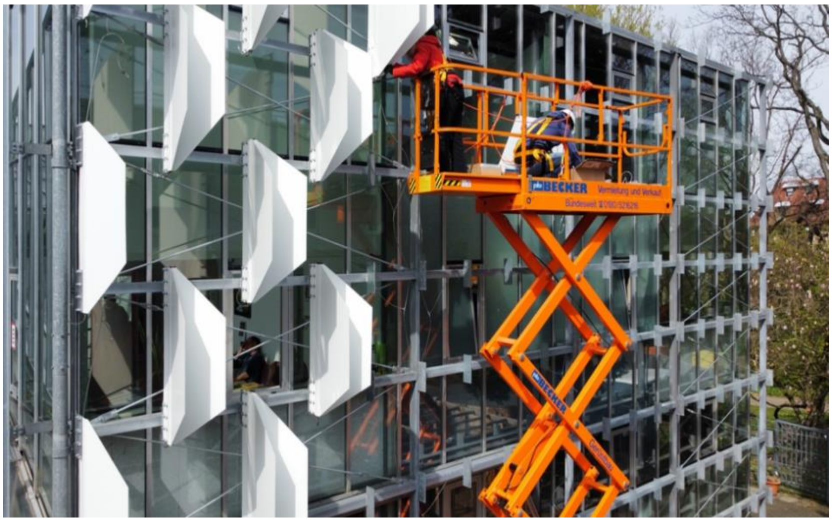


Figure 45: Initial Installation of Flectoline Modules (University of Stuttgart, Institute of Building Structures and Structural Design, 2024).

4.5.1 Results of Case Study Three

In this section, the case study of FlectoLine Facade is explored through a series of tables designed to systematically review its façade systems and smart technologies. While the structure of the tables remains consistent with Chapter 3 for comparability, this analysis focuses on the project's distinctive approach to responsive façade design and movement-based strategies. The process begins with general building information and then examines the intelligent systems integrated into the façade. It continues by assessing the environmental control methods and energy-related strategies, before concluding with a review of materials and glazing technologies. The tables present core data in a streamlined format, while the accompanying text provides deeper insight into the functions and impact of each system.

By organizing the information in this way, the study highlights the unique qualities of FlectoLine Facade and establishes a solid foundation for comparison with the other case studies presented later in this chapter.

Table 10: General Information of FlectoLine Façade (Author, 2025).

Category	Details
Location	Botanical Garden, University of Freiburg, Germany
Year of Construction	2024
Architect / Developer	University of Stuttgart – ITKE & ITFT (with Univ. of Freiburg & Univ. of Tübingen)
Function	Botanical Garden Building
Climate Zone	Temperate Oceanic
Height / Floors	Approx. 8–10 m / 2 floors
Construction Area	Façade coverage: 83.5 m²
Structural System	Fiber-reinforced composite plates with built-in hinge zones and integrated pneumatic cushion actuators
Building Skin Type	Single skin facade

Table 10 summarizes the location, façade type, and main characteristics of the FlectoLine Facade. Developed as part of an academic research project, this prototype represents an innovative and environmentally responsive façade solution aimed at improving existing buildings. These general details provide a foundation for the analysis of intelligent control systems, environmental control strategies and materials presented in the following tables.

Table 11: Intelligent Building Systems of FlectoLine Façade (Author, 2025).

System Category	Technologies Implemented
Control System	Closed-loop system with ML-based decision-tree algorithm
Sensors	Embedded sensors for light, temperature, and wind data
IoT (Internet of Things)	Not implemented as a full platform; local data handling for façade control
BMS (Building Management System)	Façade control unit only

Table 11 summarizes the intelligent building systems integrated into the FlectoLine Facade. The façade operates through a closed-loop control mechanism, using a machine learning decision-tree algorithm to adjust the movement of panels throughout the day. This enables the system to respond dynamically to changing environmental conditions and optimize performance.

Embedded sensors collect key data on light levels, temperature, and wind conditions, which are combined with weather forecasts and predicted energy demand to inform control decisions. While there is no explicit IoT cloud connectivity, all data is processed locally within the façade's dedicated control unit. Similarly, a full-building BMS is not present; instead, a localized façade control unit independently manages the FlectoLine system without integrating with other building operations.

Table 12: Environmental Control & Energy Systems of FlectoLine Facade (Author, 2025).

System Category	Technologies Implemented
Solar Collector & PV Panels	BIPV integrated with real-time digital twin for lighting, thermal, and energy simulations
Solar Control Systems	Responsive shading via pneumatic-actuated panels; controls brightness, glare, and indoor temperature

Table 12 highlights the environmental control and energy strategies integrated into the FlectoLine Facade. The system combines building-integrated photovoltaics (BIPV) with a real-time digital twin, enabling continuous simulation of lighting, thermal behaviour, and energy production to optimize façade performance.

Responsive shading is achieved through pneumatic-actuated panels, which dynamically adjust to maintain brightness, reduce glare, and regulate indoor temperature. This approach creates a balance between occupant comfort and energy efficiency while supporting on-site renewable energy generation.

Table 13: Materials and Glass Systems of FlectoLine Facade (Author, 2025).

System Category	Technologies Implemented
Energy-Efficient Glazing	Standard greenhouse glazing behind the façade (daylighting and thermal insulation)
Smart Glass	Not used
Smart Materials	Flexible composite panels with built-in hinge zones and pneumatic actuators; two material types: (1) hybrid composite with elastic & stiff layers, (2) thermoplastic

Table 13 summarizes the material strategy of the FlectoLine project. The base greenhouse structure relies on **s**tandard glazing to provide daylight and basic thermal insulation. In front of this, the FlectoLine system acts as a dynamic shading layer, built from flexible composite panels with integrated pneumatic actuators. These panels bend smoothly without mechanical hinges, using two bio-inspired material types to achieve movement. Tested for durability and outdoor performance, this setup demonstrates how innovative materials can enable responsive façades that enhance comfort and energy performance.

In summary, the FlectoLine Facade demonstrates how advanced research and bio-inspired design can create a highly adaptive and responsive shading system. Unlike the other case studies, FlectoLine is not a complete building but a retrofit demonstrator attached to an existing greenhouse. Through the integration of flexible composite panels, pneumatic actuation, and a digital twin, the system continuously adjusts to changing environmental conditions.

The analysis of the tables shows that while there is no full IoT network or building-wide BMS, a localized closed-loop control unit effectively manages panel movement using data from embedded sensors and weather forecasts. This enables real-time balancing of daylight, glare reduction, indoor temperature, and on-site renewable energy generation via BIPV integration. By combining smart materials and advanced control strategies, FlectoLine provides a model for how future façades can achieve both sustainability and user comfort in retrofit applications.

This case study forms the final part of the analysis and sets the stage for the comparative evaluation in the next chapter, where FlectoLine will be examined alongside The Edge and BIQ House to highlight different approaches to intelligent building skins.

4.6. Selected Case Four: Cube Berlin

Location: Berlin, Germany

Year of Construction: 2020

Architect: 3XN Architects

Function: Office Building

Designed by Copenhagen-based 3XN Architects, the 11-story Cube Berlin is located in Washingtonplatz, near the city’s central train station, and has a total gross floor area of 19,000 square meters. Each floor ranges from 300 to 1,400 square meters, offering flexible, future-oriented office solutions to meet the evolving needs of its users. To achieve a high level of digitalization, the developer CA Immo partnered with Drees & Sommer, which provides consulting, planning, and project management services (Sweet, 2018). The opening of Berlin’s Main Railway Station in 2006 marked the beginning of “Europa City,” a major new urban development project within the city. Washington Platz has since become both a central gateway for visitors arriving in Berlin and a key location for contemporary urban growth.

Because the site is fully exposed on all sides, the form and building skin of Cube Berlin were critical design considerations. The goal was to create a structure with a sculptural and distinctive presence that would complement, rather than overshadow, the Main Railway Station. In response, 3XN Architects developed a relief-patterned, reflective building skin designed to capture and refract the surrounding environment, producing a dynamic, kaleidoscopic visual effect that enhances the building’s integration with its context (3XN, n.d.).

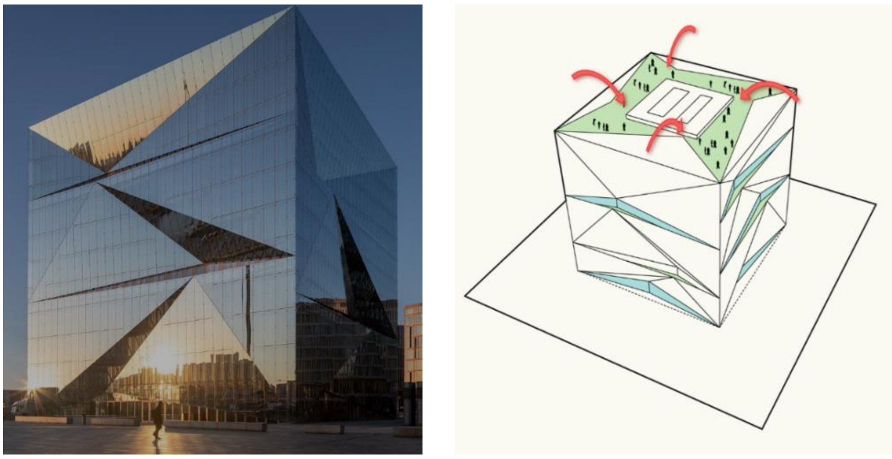


Figure 46: Cube Berlin (3XN, n.d.).

What makes Cube Berlin stand out is not only its striking modern architecture but also its artificial intelligence (AI)-based smart management system. This system creates an intelligent network connecting all building equipment and sensors with the central control unit. By analysing environmental conditions, user behaviour, and operational data, the system is able to learn and continuously generate suggestions to improve building performance. For instance, according to CA Immo, unused spaces do not require heating, ventilation, or lighting because the system detects occupancy levels and automatically turns these services off when no one is present. Once someone enters the area, the system reactivates the necessary functions. Additionally, tenants can use a mobile application to manually override the central system, allowing them to adjust climate control, access, and other services based on their personal needs (Sweet, 2018).

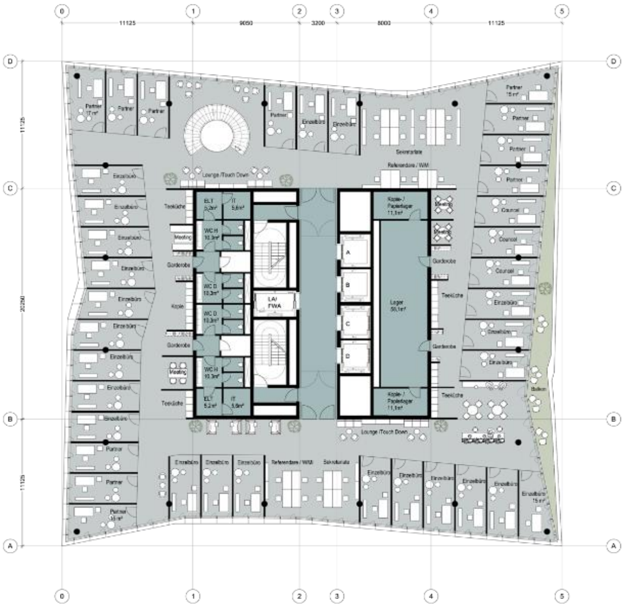


Figure 47: Floor Plan of Cube Berlin

With one side of the building surrounded by a dense urban fabric and the other opening towards the Government Complex with a wide open space, the design required a distinct and innovative architectural solution. In response, the building skin was given a dynamic character. The building is enclosed by an outer glass skin with a triangular pattern, which works together with a stepped thermal building skin beneath it to create depth and a sense of movement. Access to the building is provided through tent-like openings placed on all four sides and at different floor levels. This design creates a fluid connection between interior and exterior spaces, enhancing interaction with the surrounding environment. As a result, the ground floor becomes active and engaging, while also offering access to outdoor platforms on every level. In addition, each side of the building presents a distinct appearance, giving the structure a unique character. Although it appears highly complex, the layered building skin is actually composed of only 12 different glass elements, arranged in varying combinations throughout the building and across both layers. The interaction between these two layers creates reflections that offer a kaleidoscopic view of the surroundings, while also forming spacious platforms within the building skin. These platforms are distributed horizontally and vertically around the building, making the building skin visually dynamic and ensuring that every viewpoint offers a unique perspective (3XN, n.d.).

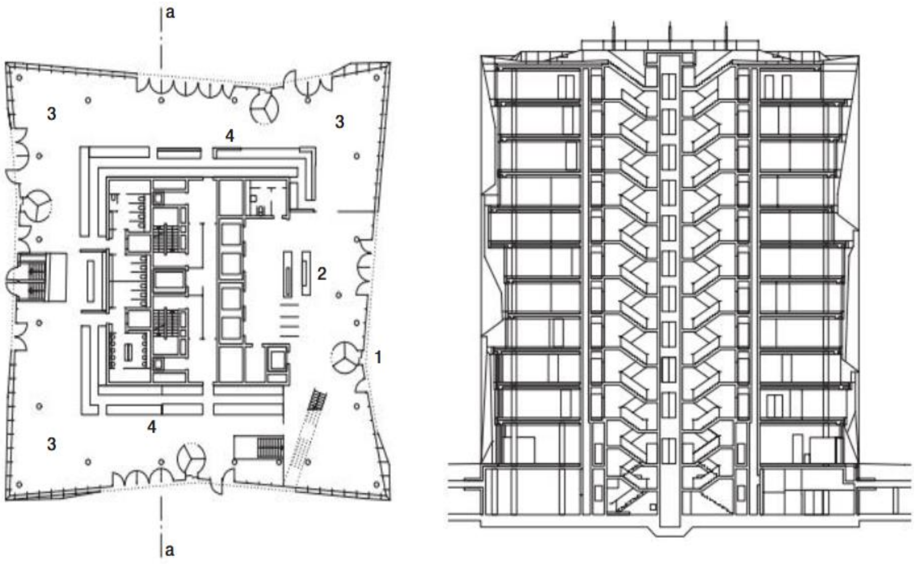
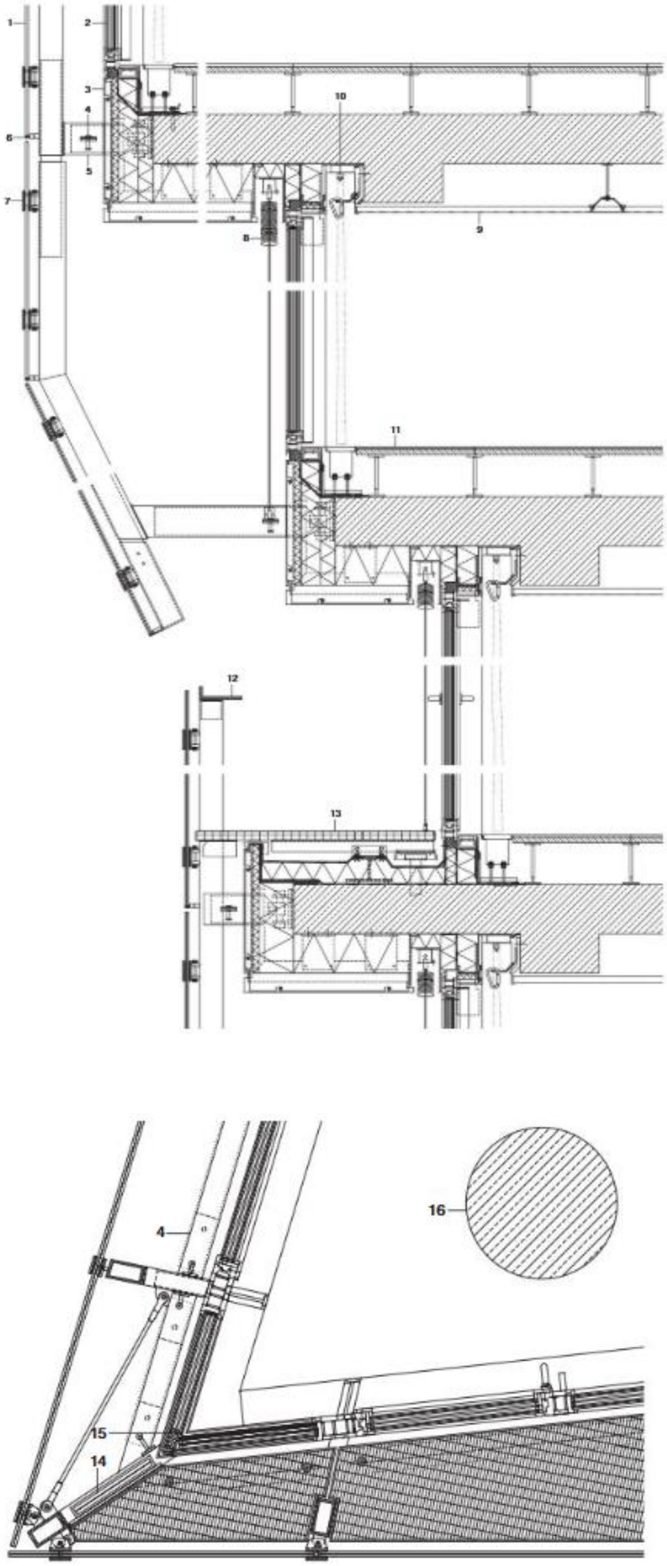


Figure 48: Ground Floor Plan and Section A-A Drawing of Cube Berlin.

The triangular glass sections of the external skin are designed to tilt both inward and outward, creating openings that allow air to circulate between the outer single-glass layer and the inner triple-glass, thermally insulated building skin. Excessive internal heat is controlled not only through this natural ventilation but also by using a special sun-reflective coating and a solar-absorbing PVB film applied to the glass skin. Additionally, to improve the durability of the glass panels and prevent issues such as delamination or discoloration, the manufacturer included an extra structural intermediate layer within the outer laminated glass skin (3XN, 2020).



Sections
scale 1:20

1 2× 10 mm low-iron laminated
sunscreen glazing with PVB foil
60/120 mm steel RHSs
2 low-E triple glazing:
2× 4 mm laminated safety glass +
14 mm cavity + 4 mm toughened
glass + 14 mm cavity +
2× 4 mm laminated safety glass
$U_g = 0.6\ \mathrm{W/m^2k}$
120/50 mm aluminium RHS posts
3 2 mm sheet aluminium
35 mm fixing rail; 3 mm sheet
thermal insulation
4 80/20 mm steel flat bracing
5 60/160 mm steel RHS
6 2 mm steel glass fixing
7 pivoting stainless-steel
glass fixing
8 80 mm aluminium venetian blind

9 4 mm sheet-steel suspended soffit
10 curtain rail
11 carpet; 10 mm raised gypsum
fibreboard with ventilation outlet
12 75/200 coated-steel-angle handrail
13 45 mm galvanized-steel grating
60/5 mm steel flat section
sealing layer
100–130 mm foamed glass
thermal insulation
vapour-retarding layer
250 mm reinforced concrete floor
200 mm mineral-wool thermal
insulation
fixing rail
95 mm aluminium cassette
3 mm aluminium sheeting
14 2× 12 mm laminated safety glass
bulkhead
15 polythene-foam strip
16 Ø 500 mm reinforced concrete
column

Figure 49: 1:20 Section Detail of The Edge (3XN, 2020).

The compact building form and efficient building skin-to-floor area ratio allow for a fully glazed exterior. The ventilated double-skin façade system provides high performance in bringing natural daylight into the interior while offering strong protection against heat gain and enabling users to benefit from natural ventilation. The building skin is integrated into a hybrid energy management system based on energy transfer principles, where excess heat from one area is redirected to cool another space, optimizing overall building performance (3XN, n.d.).

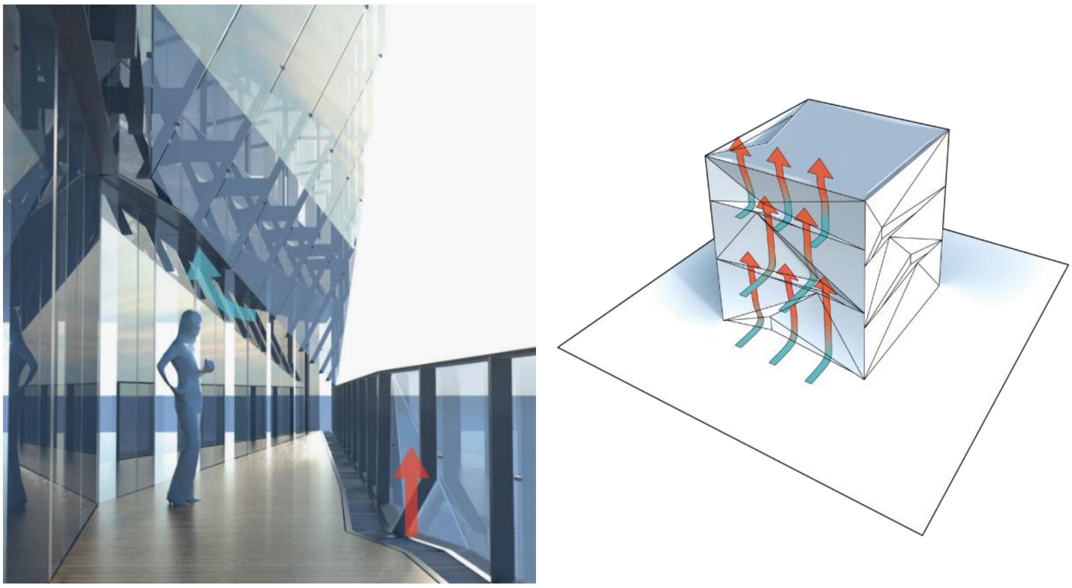


Figure 50: Integrated Energy Concept of Cube Berlin (3XN, n.d.).

In addition, Cube Berlin sets a new standard with the integration of smart digital user interfaces. The building is designed to respond to user needs and habits, creating an interactive experience while promoting energy efficiency. The intelligent building system operates through a self-learning “brain” that coordinates everyday functions such as access control, elevators, climate systems, lighting, and room reservations. By connecting all these systems, it provides a more efficient and user-friendly experience. Through a mobile application, users and visitors can interact with the building in various ways. Beyond simply opening doors or calling elevators, the app encourages sustainable behaviour, connects people, and helps them select workspaces based on personal preferences, colleague locations, and real-time energy performance (3XN, n.d.).

Figure 51: An Interior View of The Edge (3XN, 2020).

4.6.1. Results of Case Study Four

This section focuses on the case study of Cube Berlin, providing a structured evaluation of its building skin and integrated smart technologies. The tables are organized in line with the framework presented in Chapter 3, ensuring consistency across all case studies and allowing for clear and direct comparisons. The analysis begins with general information about the building, followed by an examination of the intelligent control systems managed by artificial intelligence and real-time data processing. It then explores the environmental control strategies and energy management approaches, concluding with an assessment of the materials and glazing solutions used in the building skin. By presenting key information in a clear and concise format, supported by detailed explanations, this section highlights Cube Berlin's innovative approach to intelligent building skins. This structured presentation also provides a strong foundation for comparing Cube Berlin's performance with that of the other projects analysed later in this chapter.

Table 14: General Information of Cube Berlin (Author, 2025).

Category	Details
Location	Washingtonplatz, Berlin, Germany
Year of Construction	2020
Architect / Developer	3XN Architects (Copenhagen) / CA Immo
Function	Office Building
Climate Zone	Temperate Oceanic
Height / Floors	11 floors
Construction Area	19,000 m² (gross floor area)
Structural System	Core-and-column reinforced concrete frame
Building Skin Type	Double-skin façade, fully glazed exterior

Table 14 provides an overview of the location, building skin type, and key features of Cube Berlin. Designed as a highly digitalized and interactive office building, Cube Berlin represents a modern approach to intelligent building skins with a focus on adaptability and energy efficiency. These general details form the basis for the subsequent analysis of environmental control strategies, intelligent control systems, and material strategies, which are further explored in the following tables.

Table 15: Intelligent Building Systems of Cube Berlin (Author, 2025).

System Category	Technologies Implemented
Control System	Closed-loop control with AI integration
Sensors	Integrated sensors for occupancy, temperature, lighting, and environmental data
IoT (Internet of Things)	Fully integrated IoT network connecting all building systems through a mobile application
BMS (Building Management System)	Central BMS with smart system coordination

Table 15 summarizes the intelligent building systems integrated into Cube Berlin. The building operates through a highly advanced AI-driven control system that connects all building equipment and sensors to a central “brain.” This system continuously analyses environmental conditions, user behaviour, and operational data to optimize building performance. By learning from patterns over time, it can make real-time adjustments and generate suggestions for improving efficiency and user comfort.

A wide network of sensors monitors factors such as occupancy, temperature, and lighting needs, enabling precise and responsive management of interior conditions. Through IoT connectivity, these sensors communicate with various systems, including HVAC, lighting, and access control, creating a fully integrated intelligent environment. Additionally, the Building Management System (BMS) serves as the core platform, coordinating all functions and allowing users to interact with the building via a mobile application. This integrated approach enhances energy efficiency, user experience, and the adaptability of the building skin.

Table 16: Environmental Control & Energy Systems of Cube Berlin (Author, 2025).

System Category	Technologies Implemented
Heat Transfer System	Hybrid energy management system that redistributes excess heat from one zone to another for cooling or heating
Solar Control Systems	Sun-reflective coatings and solar-absorbing PVB film integrated into double-skin façade for passive shading

Table 16 outlines the environmental control and energy strategies integrated into Cube Berlin’s building skin. The structure features a hybrid energy management system that redistributes excess heat from one area of the building to another, optimizing overall performance by balancing heating and cooling demands.

For solar control, the double-skin façade incorporates sun-reflective glass coatings and a solar-absorbing PVB film, which together minimize unwanted heat gain while still allowing natural daylight to enter the building. This passive approach enhances energy efficiency and provides visual comfort for occupants without relying on external shading devices or complex moving elements.

These integrated strategies work collectively to reduce energy consumption, improve indoor comfort, and support the building's goal of operating as a highly efficient and intelligent structure.

Table 17: Materials and Glass Systems of Cube Berlin (Author, 2025).

System Category	Technologies Implemented
Energy-Efficient Glazing	Triple-glazed, thermally insulated inner skin and single-glass outer skin with ventilation gaps
Smart Glass	Not applied, but outer glass incorporates solar-absorbing PVB film
Smart Materials	Durable glass panels with intermediate structural layer to prevent delamination and discoloration

Table 17 summarizes the material and glazing strategies used in Cube Berlin's building skin. The system features a ventilated double-skin façade with a triple-glazed, thermally insulated inner layer and a single-glass outer layer separated by ventilation gaps. This configuration enhances natural daylighting, improves thermal performance, and allows for passive cooling through natural airflow.

Although Cube Berlin does not utilize active smart glass technologies such as electrochromic or photochromic glazing, the outer glass incorporates a solar-absorbing PVB film, which helps to control solar gain and reduce glare. Additionally, the glass panels are designed with a special intermediate structural layer to prevent issues such as delamination and discoloration, ensuring long-term durability and maintaining the building skin's aesthetic quality.

Overall, these strategies create a high-performance building skin that balances transparency, energy efficiency, and visual comfort while supporting the building’s adaptive and sustainable design approach.

In conclusion, Cube Berlin integrates a fully digitalized intelligent building skin, combining a ventilated double-skin façade system with AI- and IoT-based control technologies. The outer single-glass layer and the inner triple-glazed, thermally insulated layer are separated by ventilation gaps, allowing natural cooling and efficient daylight penetration into the interior. This design limits unwanted heat gain while supporting user comfort through natural ventilation.

Solar control is achieved with sun-reflective coatings and a solar-absorbing PVB film, while an intermediate structural layer is added to the glass panels to prevent issues such as delamination and discoloration, increasing durability and long-term performance.

Operationally, the building is managed by a self-learning central “brain” that analyses data from sensors monitoring temperature, light, and occupancy. This data enables the real-time optimization of HVAC, lighting, shading, and access systems. Through a mobile application, users can adjust indoor conditions based on personal preferences, while the Building Management System (BMS) ensures overall optimization and fault detection. In addition, a hybrid energy management system redistributes excess heat to different areas, helping to balance heating and cooling demands efficiently.

Through this integrated approach, Cube Berlin demonstrates a building skin that is transparent yet protective, and flexible yet resilient. Its geometry and glass design create visual comfort and environmental balance, while the control systems enhance adaptability and user experience. The material strategy supports long-term performance and sustainability, making Cube Berlin a strong reference point for future intelligent, energy-efficient, and user-centered building skins.

4.7 Comparison of Case Studies

This section presents a comparative analysis of the three case studies: The Edge, BIQ House, FlectoLine Façade and Cube Berlin. Each project represents a distinct approach to intelligent building skins, ranging from fully integrated intelligent office environments to experimental bio-reactive and retrofit systems. The aim of this comparison is to examine how different strategies address key performance criteria, including user comfort, energy efficiency, environmental impact, safety, durability, and sustainability. This section presents a comparative analysis of the four case studies: The Edge, BIQ House, FlectoLine Façade and Cube Berlin. Each project represents a distinct approach to intelligent building skins, ranging from fully integrated smart office environments to experimental bio-reactive and retrofit systems. The aim of this comparison is to examine how different strategies address key performance criteria, including user comfort, energy efficiency, environmental impact, safety, durability, and sustainability.

The analysis is structured using the same framework applied in the previous chapters, ensuring that each case study is evaluated consistently. By comparing the data presented in the tables, similarities and differences can be identified in terms of intelligent systems, environmental control, and material strategies. This systematic approach provides insight into how context, function, and technology influence the design and performance of intelligent building skins.

Table 18: General Information of the Case Studies (Author, 2025)

Category	The Edge	BIQ House	FlectoLine Facade	Cube Berlin
Location	Amsterdam, Netherlands	Hamburg, Germany	University of Freiburg, Germany	Washingtonplatz, Berlin, Germany

Year of Construction	2014	2013	2024	2020
Architect / Developer	PLP Architecture	Splitterwerk Architects (with Arup)	University of Stuttgart – ITKE & ITFT (with Univ. of Freiburg & Univ. of Tübingen)	3XN Architects (Copenhagen) / CA Immo
Function	Office (Deloitte HQ)	Residential (Pilot Project)	Botanical Garden Building	Office Building
Climate Zone	Temperate Oceanic	Temperate Oceanic	Temperate Oceanic	Temperate Oceanic
Height / Floors	15 floors / 58 m atrium	5 floors (including penthouse)	Approx. 8–10 m / 2 floors	11 floors
Construction Area	40,000 m²	1,600 m²	Façade coverage: 83.5 m²	19,000 m² (gross floor area)
Structural System	Steel-reinforced concrete	Stone and reinforced concrete	Fiber-reinforced composite plates with built-in hinge zones and pneumatic cushion actuators	Steel-reinforced concrete with hybrid double-skin façade structure
Building Skin Type	Single skin façade	Double skin façade with bio-reactive SolarLeaf panels	Single skin façade	Double-skin façade, fully glazed exterior

Table 18 provides a summary of the key characteristics of the three case studies, offering a clear overview of their context and building skin types. This information forms a fundamental basis for understanding how each project approaches the design and performance of intelligent building skins.

Table 19: Intelligent Building Systems of the Case Studies (Author, 2025)

System Category	The Edge	BIQ House	FlectoLine Facade	Cube Berlin
Control System	Closed-loop control	Closed-loop control	Closed-loop control with ML algorithm	Closed-loop control with AI integration
Sensors	Light, thermal, motion sensors; user check-in via Mapiq	Sensors inside algae panels (CO_2, temp, light, water quality)	Sensors for light, temperature, wind	Occupancy, light, temperature, and environmental sensors

IoT	Full IoT integration via Mapiq app and networked devices	Not implemented	Not implemented; local data only	Full IoT integration with app-based user interaction
BMS	Schneider BMS for centralized building management	Limited Energy Management Centre (façade & thermal storage)	Local façade control unit only	Central BMS with smart system coordination

Table 19 compares the intelligent systems of the four case studies. The Edge represents a fully integrated intelligent building, featuring a closed-loop control system, a wide range of sensors, full IoT connectivity through the Mapiq platform, and a comprehensive BMS for centralized management. BIQ House, by contrast, focuses on its bio-reactive façade, using internal sensors and a localized Energy Management Centre without IoT integration. FlectoLine also relies on a localized closed-loop control unit enhanced by machine learning, but it operates independently without full IoT or building-wide BMS integration.

Cube Berlin stands out with its AI-driven control system, which connects all sensors and building equipment to a central platform. Through this system, environmental conditions, user behavior, and operational data are continuously analyzed to optimize energy use and enhance user comfort. IoT integration enables real-time interaction between users and the building via a mobile application, while the BMS manages daily functions such as lighting, access control, and climate systems.

From this comparison, it becomes clear that there is a spectrum of approaches to intelligent building skin management. The Edge demonstrates how complete digital integration can optimize both building-wide performance and user experience. Cube Berlin similarly showcases advanced integration, with a strong focus on adaptability and interactive features. BIQ House, while more limited, shows how targeted systems can successfully manage specialized functions like bio-reactive energy generation. FlectoLine represents a research-driven, adaptive solution that pushes innovation in material and control technology but remains focused on façade-level performance. Together, these cases highlight how the degree of technological integration directly shapes the scope and impact of intelligent building systems.

Table 20: Environmental Control & Energy Systems of the Case Studies (Author, 2025)

System Category	The Edge	BIQ House	FlectoLine Facade	Cube Berlin
Solar Collector & PV Panels	1,920 m² PV on roof; 2,280 m² PV on nearby roofs	129 algae panels; heat + hot water + biogas	BIPV with real-time digital twin	Heat redistribution system, no solar collection
Solar Control Systems	South PV panels; east/west operable windows	Algae panels for shading, insulation, noise	Responsive pneumatic panels for shading	Reflective coating + automated shading in double-skin façade

Table 20 compares the environmental control and energy systems of the four case studies. The Edge demonstrates large-scale PV integration combined with operable building skin elements for ventilation. BIQ House uses algae panels for both energy production and shading, offering a multifunctional building skin solution. FlectoLine combines BIPV with responsive pneumatic shading, presenting a high-tech, adaptive approach. In contrast, Cube Berlin focuses on heat redistribution within its double-skin façade rather than solar energy collection, utilizing reflective coatings and automated shading to enhance thermal comfort and energy efficiency. This comparison highlights diverse strategies for optimizing energy performance and solar control in intelligent building skins.

Table 21: Materials and Glass Systems of the Case Studies (Author, 2025)

System Category	The Edge	BIQ House	FlectoLine Facade	Cube Berlin
Energy-Efficient Glazing	Low-e glass on all façades; thicker on north for noise control	Four-layer glass for algae culture and heat loss reduction	Greenhouse glazing for daylight and insulation	Triple-glazed inner skin + single-glass outer skin with ventilation gaps
Smart Glass	Not used	Not used	Not used	Not used
Smart Materials	PV panels for energy and shading	SolarLeaf algae panels for energy and CO_2 absorption	Flexible composite panels with pneumatic actuators	Reinforced glass panels with protective layer

Table 21 compares the material and glazing strategies of the four case studies. The Edge uses conventional low-emissivity glazing and integrates PV panels for both energy production and shading, offering a balanced solution between performance and cost. BIQ House goes a step further by incorporating bio-reactive SolarLeaf panels, which generate energy, absorb CO_2, and provide shading and insulation, making the building skin an active, living system. FlectoLine introduces an experimental approach with flexible composite panels and pneumatic actuators, emphasizing responsive movement and adaptability rather than direct energy generation. Cube Berlin, on the other hand, combines a triple-glazed inner skin with a single-glass outer skin that includes a solar-absorbing PVB layer, enhancing thermal performance and solar control. Its durable glass panels feature a reinforced intermediate layer to prevent structural issues such as delamination and discoloration, ensuring long-term building skin quality. This comparison highlights how material choices influence the role and performance of intelligent building skins. The Edge demonstrates efficiency through established technologies, BIQ House showcases multifunctionality through bio-integration, FlectoLine pushes innovation with advanced responsive materials, and Cube Berlin focuses on durability, adaptability, and user comfort through its advanced glazing system. Together, these cases reflect a spectrum from conventional to highly experimental approaches in intelligent building skin design.

Table 22 summarizes the overall performance of the three case studies according to the final QEM criteria. Each criterion is evaluated using three levels high, medium, and low to indicate the relative strength of each project. The accompanying keywords briefly explain the reason for each rating, while detailed justifications are provided in the text below.

Table 22: Comparative Assessment of Case Studies Using QEM Criteria (Author, 2025).

Criteria	**The Edge**	**BIQ House**	**FlectoLine Facade**	**Cube Berlin**
Human Comfort	High – Natural ventilation, operable windows, personalized control	Medium – Passive shading, thermal insulation, limited adaptability	High – Adaptive shading, glare control, thermal regulation	High – Personalized climate control via AI and app integration
Energy Efficiency	Very High – PV + thermal energy storage	Very High – Algae energy + geothermal storage	Medium – Limited BIPV area with real-time optimization	High – Heat redistribution system, energy optimization
Cost	Medium – High initial cost, lower operational cost	Low – Experimental tech, high maintenance cost	Low – Prototype system, high development cost	Medium – Advanced tech with balanced operational costs
Environmental Impact	High – CO_2 reduction, sustainable design, BREEAM certified	Very High – CO_2 absorption, renewable cycle	Medium – Energy savings through shading	High – Smart energy use, reduced waste through adaptive systems
Safety	High – Integrated fire & structural safety	Medium – Basic safety systems	Medium – Façade-level safety testing	High – Advanced monitoring and safety sensors
Durability / Maintainability	High – Robust materials, planned maintenance	Low – Frequent cleaning, high upkeep needs	Medium – Weather-tested, still experimental stage	High – Durable glass panels with intermediate layer
Sustainability	High – Long-term performance, certified strategies	High – Carbon-neutral approach, renewable focus	Medium – Limited scalability and lifecycle data	High – Long-term adaptive performance and energy efficiency

Intelligence (Adaptivity)	Very High – Full IoT + BMS integration	Low – Local system, no full integration	High – Machine learning-based façade control	Very High – AI-driven system with full connectivity

Table 22 provides a comprehensive evaluation of the four projects by comparing their intelligent building skin performance using QEM criteria. The strengths and weaknesses of each project are shaped not only by their technological capacity, but also by the climatic conditions of their location and their functional requirements. Therefore, the assessment highlights not just the success of the technologies used, but also how these technologies operate within a specific context and reflect certain design priorities.

The Edge, located in Amsterdam's temperate oceanic climate, is a large-scale office building. This context creates complex and constantly changing requirements, especially in terms of user comfort and energy efficiency. High occupancy levels, diverse usage patterns throughout the day, and dynamic energy demands require advanced IoT integration and BMS control. The Edge's large atrium provides natural ventilation and daylight, while PV panels on the south building skin contribute to energy generation, and the east and west façades include elements for natural ventilation and glare control. This holistic strategy positions The Edge as a leader in Human Comfort, Energy Efficiency, Intelligence, Durability, and Safety. However, its high initial investment cost is a notable limitation. Over time, though, this is offset by reduced operational costs and optimized energy performance, making it a viable long-term solution.

BIQ House, located in Hamburg's similar climate, is a residential, experimental project. It was developed with a focus on environmental sustainability and individual user comfort. The SolarLeaf algae panels not only generate energy but also absorb

CO_2, creating a direct interaction between the building and its environment. This unique feature gives BIQ House strong performance in Environmental Impact and Sustainability. However, the absence of a fully integrated intelligent control system and the high maintenance needs of the panels limit its performance in Intelligence, Durability, and Human Comfort. As such, BIQ House should be viewed as a pilot project that pushes the boundaries of sustainable design, rather than a fully scalable solution.

FlectoLine Building Skin, located at the botanical garden in Freiburg, is a two-story experimental prototype. Rather than serving as a fully functional building, it was designed as a platform to test adaptive building skin technologies. Its machine learning-based closed-loop control system optimizes shading and energy generation in real time. This makes FlectoLine stand out particularly in Human Comfort and Intelligence (Adaptivity). However, the system currently operates at a local level and has not yet been integrated into a complete building. While its materials have been weather-tested, long-term performance data is still limited. Therefore, FlectoLine should be considered a vision of the future for data-driven, fully adaptive building skins, rather than a ready-to-deploy solution for today.

Furthermore, Cube Berlin, located in Berlin’s temperate oceanic climate, is a mid-rise office building designed to showcase the potential of fully digitized and user-centred intelligent building skins. Its location in a highly visible urban square, surrounded by dense development and open public spaces, required a dynamic architectural and functional response. The double-skin façade plays a central role in this design, combining a stepped inner thermal layer with an outer glass skin that features reflective coatings and automated shading systems. Instead of relying on solar collection for energy generation, Cube Berlin focuses on optimizing heat redistribution within the building, improving overall energy efficiency. The building integrates a highly advanced AI-based central control system that continuously learns from environmental data, user behaviour, and operational patterns. Through a mobile application, users can interact with the building to manage functions such as access, climate control, and lighting. This seamless integration positions Cube Berlin strongly in Intelligence and Human Comfort, as it provides personalized experiences while maintaining energy efficiency. However, Cube Berlin does not include renewable energy generation like PV panels or bio-reactive systems, which slightly limits its environmental contribution compared to other case studies. While its durability and maintainability are supported by robust materials and centralized management, the high initial cost of such advanced systems remains a challenge. Overall, Cube Berlin represents a cutting-edge example of a intelligent office building where technology, user engagement, and building skin performance are fully intertwined, setting a benchmark for future intelligent building designs.

Even though all four projects are located in temperate oceanic climates, the differences in their functions and design priorities play a decisive role in shaping their building skin strategies. The Edge, as a large-scale office building, requires a highly complex and fully integrated system to respond to constant changes in internal conditions, diverse usage patterns, and high occupant turnover. Cube Berlin, also an office building but on a smaller scale, focuses on digital connectivity and user interaction, utilizing AI-based systems to optimize comfort and energy use without relying on renewable energy generation. BIQ House, operating at a residential scale, prioritizes individual comfort and environmental sustainability, integrating bio-reactive SolarLeaf panels to generate energy and absorb CO_2. Finally, FlectoLine, as an experimental prototype, is designed to test adaptive materials and machine learning-based control systems rather than meet conventional functional demands.

This comparison demonstrates that climate alone is not sufficient to guide building skin design; factors such as building function, user behaviour, and technological integration are equally important in determining strategies. While The Edge represents large-scale, comprehensive system integration, Cube Berlin focuses on intelligent user experience and operational efficiency, BIQ House emphasizes environmental responsiveness, and FlectoLine showcases the future potential of fully adaptive systems.

When viewed as a whole, each project emerges as a leader in different domains. The Edge represents a scalable, integrated technological model that optimizes building-wide performance and user comfort. Cube Berlin demonstrates how AI-driven systems and interactive digital interfaces can enhance user engagement and operational adaptability. BIQ House offers a visionary approach where the building skin directly interacts with natural systems, embodying environmental sustainability. FlectoLine highlights the potential of next-generation adaptive, data-driven façades, setting a benchmark for future innovations.

The ideal intelligent building skin of the future would merge the unique strengths of these projects into a unified strategy. This would mean combining The Edge’s advanced system integration and real-time building-wide control, Cube Berlin’s focus on digital connectivity and user interaction, BIQ House’s environmentally conscious, bio-reactive systems, and FlectoLine’s adaptive, machine learning-based control. By integrating these complementary elements, it becomes possible to design building skins that generate energy, adapt dynamically to real-time environmental data, minimize environmental impact, and continuously evolve to meet future technological and social needs.

In conclusion, the comparison of these four case studies demonstrates that intelligent building skins must go beyond current performance expectations to address future challenges in technology, sustainability, and human experience. This holistic perspective provides a roadmap for creating long-term, adaptable, and sustainable building skins, shaping the next generation of architectural design.

Chapter 5

CONCLUSION

The analysis of The Edge, BIQ House, FlectoLine, and Cube Berlin projects reveals how diverse strategies, technologies, and design priorities converge to shape the future of intelligent building skins. Each project addresses critical aspects such as user comfort, energy performance, sustainability, and adaptability in its own unique way, providing valuable insights into how building skins can evolve to meet both current and future demands. The findings demonstrate that building skin details are not isolated design choices but rather the outcome of broader, interconnected strategies involving technology integration, environmental objectives, and functional needs. For example, the advanced building management system (BMS) and IoT-based control mechanisms at The Edge directly influence the design of building skin components from operable windows to automated shading devices enabling real-time responses to user data and climate conditions. Similarly, BIQ House's SolarLeaf panels function not only as façade elements but also as active components of a closed environmental cycle. This dual role impacts material selection, maintenance strategies, and energy generation capacity.

FlectoLine, as an experimental prototype, focuses on adaptive, machine learning-based modules that redefine the relationship between the building skin, movement, and environmental interaction. This project illustrates how future building skins could evolve into fully dynamic, self-regulating systems. Cube Berlin, on the other hand, highlights the integration of artificial intelligence and digital connectivity at a high operational level. While it does not generate renewable energy through its building skin, it excels in user interaction and operational adaptability. Its smart digital platform connects sensors, building equipment, and user interfaces, allowing the skin to respond to occupancy levels and usage patterns while optimizing comfort and energy efficiency in real time.

Collectively, these four case studies show that intelligent building skin details from glazing types and panel configurations to sensor locations and material compositions emerge from the complex interplay between climate, building function, technology, and user expectations. High-performance building skins go beyond visual expression or surface coverage; they function as fully integrated systems that balance passive and active strategies to enhance comfort, efficiency, and durability.

In practical terms, this means that the building skins of the future must evolve beyond conventional curtain walls or static envelopes. Real-time data processing, renewable energy integration, and adaptive components need to be embedded into the very fabric of the building skin, transforming sustainability and intelligent building concepts into tangible design solutions. As buildings become increasingly intelligent and environmentally responsive, the precision and innovation required in their detailing will grow exponentially.

In conclusion, an intelligent building skin operates as a multi-layered interface that simultaneously fulfills environmental, functional, and technological roles. When advanced control systems, sustainable materials, adaptive designs, and digital user platforms are combined as seen in these four case studies the building skin moves beyond its traditional role of providing protection. It becomes an active system that generates energy, enhances quality of life, optimizes operations, and responds dynamically to climate change. This integrated vision ensures that even the smallest elements, from sensors to shading devices, contribute to resilient, future-ready architectural solutions.

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