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Utilization of Intelligent Facade Technologies in High-rise Office Buildings: A Comparative Study

Fazilet Tuğrul Okbaz *
Simay Aydinç**
Ferhat Pakdamar***

Abstract

In the late 19th century, spurred by the Industrial Revolution and the concomitant rise in population and technological advancements, high-rise buildings began to emerge in urban centers. Initially, concerns regarding the environmental impacts of these structures were not at the forefront. However, the advent of sustainability debates in the 1970s elevated this discourse, particularly regarding high-rise buildings. This progression notably influenced the materials and facade systems of high-rise structures. Alterations in building facades subsequently catalyzed the development of adaptive building coatings that consider environmental factors, climate variations, and user preferences. Termed as intelligent facade systems, these innovative facades aim to enhance indoor comfort and diminish energy consumption. Integration of control and sensing technologies into facades has rendered them multifunctional components. The amalgamation of diverse technologies has rendered the concept of intelligent facades intricate, thereby complicating a definitive definition. This study scrutinizes the employment of intelligent facade systems in high-rise buildings, offering a fresh perspective by proposing a classification in line with existing definitions and classifications in the literature. It categorized the changes introduced by integrated devices and mechanisms into five groups: passive, mechanical, electro-mechanical, integrated technology, and information technology. Additionally, changes resulting from materials are classified under energy and property-transforming materials. Based on the new proposed classification, a comprehensive comparative analysis of 20 high-rise office buildings, encompassing 10 from Turkiye and 10 from across the globe, was conducted. The investigation revealed passive technologies as the prevailing systems employed in high-rise building facades, both domestically in Turkiye and worldwide. Integrated technology is the second most utilized system after passive technology. Based on all the investigations conducted, it can be concluded that energy-changing materials are employed in a greater number of buildings worldwide compared to Turkiye. However, there is still concurrent progress in facade technology.

Keywords:
Facade technologies, High-rise buildings, Intelligent façade, Office buildings

* Department of Architecture, Faculty of Architecture, Gebze Technical University, Kocaeli, Turkiye.
(*Corresponding author*)
E-mail: ftugrul@gtu.edu.tr

** Graduate School of Natural and Applied Sciences, Gebze Technical University, Kocaeli, Turkiye.
E-mail: simayaydinc@gmail.com

*** Department of Architecture, Faculty of Architecture, İstanbul Technical University, İstanbul, Turkiye.
E-mail: pakdamar@itu.edu.tr

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INTRODUCTION

High-rise buildings, emerging because of technological and economic advancements, represent a typology of structures that cater to the increasing needs of the population. Starting with the construction of the Home Insurance Building in Chicago in 1853 and progressing to the world's first high-rise, the Burj Khalifa, this typology has witnessed rapid advancement worldwide. Parallel to the Industrial Revolution, the economic progress of the 19th century triggered a transformation in high-rise buildings, evolving office structures into buildings that better meet the demands and comfort conditions of users. During this period, global energy crises led to prioritizing energy consumption and efficiency issues in building design.

Energy consumption in the construction sector in the United States and the European Union is significantly higher compared to other sectors (Oró et al., 2012). Dominant factors contributing to energy consumption in buildings include heating, ventilation, and lighting, which constitute approximately 46% of total energy consumption in constructed environments (Department of Energy, 2015). According to the Energy Information Agency, buildings account for approximately 41% of US Energy Consumption. Consumption in commercial buildings is mainly attributed to lighting (20%), space heating (16%), and space cooling (14%) (Sawyer, 2014) (Monthly Energy Review, 2013). According to the 'Energy Performance of Buildings Directive' published by the European Union, buildings play a significant role in energy consumption, accounting for approximately 40% of the total energy consumed in the EU (Bertoldi et al., 2019). This statistic highlights the substantial impact that buildings have on energy usage and emphasizes the need to address their energy efficiency to achieve sustainable development goals. This statistic emphasizes the significant impact of building energy usage and underscores the necessity of addressing energy efficiency to achieve sustainable development goals. Recognized as major energy consumers, buildings have a significant impact on overall energy demand and carbon emissions. Various energy-intensive activities such as heating, cooling, lighting, and operation of electrical devices contribute to the substantial energy footprint of buildings. Therefore, improving building energy performance is not only about reducing energy consumption but also vital for mitigating climate change, enhancing resource efficiency, and promoting environmental sustainability.

In evaluating energy consumption concerning building components, it becomes evident that building envelopes take precedence. The facade, constituting the outer shell of a building and segregating the interior from the external environment, serves not only as a protective element but also as a pivotal structural component with substantial influences on energy efficiency and indoor comfort. Facades of buildings play a crucial role in energy loss, accounting for approximately 20-60% of the building's total energy consumption (Balali & Valipour, 2020; Cheng et

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al., 2014). The energy loss attributed to facades stems from several factors. Firstly, when facades are constructed from materials with high thermal conductivity, they can increase heat transfer. This can lead to higher energy consumption for heating and cooling systems, consequently resulting in increased energy costs. Secondly, inadequate insulation can cause fluctuations in indoor temperature depending on external conditions, negatively impacting indoor comfort. Finally, a lack of control over sunlight and heat gain can further escalate energy losses from facades.

The facades of high-rise buildings constitute a critical component that separates indoor spaces from the external environment while endeavoring to minimize energy loss. Due to their expansive glass surfaces and heights, the facades of high-rise buildings account for a significant portion of energy consumption, necessitating a prioritization of energy-saving measures in these areas. Moreover, because high-rise building facades are more exposed to sunlight and weather conditions, there is a greater need to focus on advanced technologies and the use of smart facades to enhance energy savings and indoor comfort. This circumstance forms the primary rationale for focusing on high-rise building facades in the study.

While traditional facade systems provide limited energy and lighting performance under various environmental conditions (Selkowitz et al., 2003), research has demonstrated that active facades generated by advanced technologies can enhance performance by 40% to 65% compared to static facades (Khaled Dewidar et al., 2010). Liu et al., 2015, in their study, have found that the energy consumption of a building can be reduced by approximately 60% when an intelligent glazed facade is used instead of a static facade in the climate of Denmark Recent investigations have demonstrated that Intelligent Facade (IF) services can contribute significantly to the prevention of approximately 70-80% of energy consumption (Habibi et al., 2022). Therefore, the use of intelligent facades is an important strategy to enhance energy efficiency and minimize energy losses. Intelligent facades are designed to automatically control the entry of sunlight and heat, using energy-efficient materials and systems. These systems monitor external conditions and internal requirements through sensors, actuators, and control systems, allowing the facades to adapt their properties accordingly.

These applied technologies enable facade systems to continuously modify their functions, features, or behaviour over time in response to environmental stimuli, occupants' preferences, and needs, thereby improving thermal and visual performance of the facade (Heidari Matin & Eydgahi, 2019) Building facade systems, play an essential role in controlling the amount of heating and cooling loads since they separate the indoor and outdoor environments (Halawa et al., 2018; Thalfeldt et al., 2013). Furthermore, studies conducted on responsive facades indicate that implementing such technologies can reduce cooling load by up to 25% and heat gain by up to 80%, leading to a 15% to 20% decrease in cooling costs (Kolarevic & Parlac, 2015) For this reason, researchers have become increasingly interested in developing facade systems that reduce cooling and heating energy consumption of buildings, have the ability to adapt to environmental and climatic conditions, control ventilation and thermal heating, and balance natural lighting. These findings highlight the importance of adopting intelligent facade systems (IFS) that can respond and adapt to changing environmental factors, leading to improved energy efficiency and occupant comfort.

Although the construction of high-rise buildings in Turkiye started approximately seventy years later than worldwide, it can be said that the country has largely closed the gap in terms of following and implementing globally used technologies. Currently, many of the contemporary structural and material technologies employed worldwide are also utilized in Turkiye. At this point, the state of implementation of IFS forms the research question.

The main aim of this study is to categorize the IFSs implemented in high-rise office buildings, evaluating this new categorization by focusing on both local and international examples. The study aims to assess the status and advancements of high-rise office buildings with intelligent facade designs, for which the most information has been accessed worldwide and in Turkiye in the past 10 years, through a comparative approach. Additionally, it aims to identify the current situation in Turkiye and provide recommendations for enhancing intelligent facade applications.

INTELLIGENT FACADES AND CLASSIFICATION

The era known as the Third Industrial Revolution, or the age of information technology, has ushered in a period of rapid technological advancements s, giving rise to novel forms of human existence. Consequently, these emerging lifestyles have engendered a discernible shift in the needs and demands of individuals. On the other hand, the rapid population growth, and the depletion of natural resources, leading to an energy crisis and increased energy costs, prompted the emergence of intelligent building designs in the 1970s.

IFS, which have been developed in parallel with the emergence of user comfort and environmental awareness concepts in architecture, are a type of facade that exhibits various characteristics and can be referred to by different names in the literature. The concept of intelligent facades, refers to facade types that can adapt, transform, learn, and respond to various factors such as users, environment, and climate. These facades, known by multiple names in the literature, generally operate on similar principles. Active and passive systems drive the functionality of intelligent facades by responding to environmental stimuli and enabling changes in the facade. Since the 1970s, these facades have experienced rapid development and have

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become an indispensable system that ensures minimum energy consumption and maximum efficiency for high-rise buildings in the present day.

The term intelligent building was initially coined and implemented by the former Intelligent Buildings Institute (IBI), located in Washington, D.C., in the early 1980s. The IBI defined an intelligent building as a ‘’one which provides a productive and cost-effective environment through optimization of four basic elements: structure, systems, services and management, and the interrelationship between them.” Despite numerous efforts by various organizations to establish a universally accepted definition, there exists a wide range of definitions for building intelligence (Omar, 2018). In Europe, the European Intelligent Buildings Group (EIBG) introduced a novel definition that characterizes an intelligent building as ‘‘creates an environment which maximizes the effectiveness of the building’s occupants while at the same time enabling efficient management of resources with minimum life-time costs of hardware and facilities.’’ In Asia, the definitions focused on the role of technology for the automation and control of building functions (Wigginton & Harris, 2013) (Wong et al., 2005) illustrate in their examination of Intelligent Building research that most initial definitions focused on reducing human involvement within the building.

The terms "smart" and "intelligent" have often been used interchangeably without a clear differentiation between the two. The term ‘smart’ refers mostly to surfaces and materials, while the term ‘intelligent’ describes a complex system. There is a difference between perception, reasoning, and action ability. Smart Buildings aim to provide occupants with control while simultaneously minimizing energy consumption per occupant hour (Buckman et al., 2014). In contrast, Intelligent facades have a perception system created according to inputs, while smart facades have action-based material integration. Nevertheless, Intelligent Buildings have primarily emphasized the incorporation of intelligent systems within their infrastructure, rather than focusing on the construction itself.

Previous Classification Studies

Since the first appearance of IFS in the 1970s, many studies have been carried out to classify these systems, but since there is no common terminology for the classification of technologies applied on building facades, a clear classification has not emerged. One of the earliest attempts to classify intelligent facades was made by Fox and Yeh in 2000. They categorized the responsive/kinetic design in architecture into three areas within the context of mechanical and technological principles. These areas include structural innovation and material development, general kinetic typologies in architecture, and control mechanisms (Fox & Yeh, 2000). Structural innovation emphasizes both the implementation methods and tools for achieving a structural solution. The implementation methods include folding, sliding, expanding, and transforming. The tools can be pneumatic, chemical, magnetic, natural, or mechanical. Material development offers integrative solutions in the construction industry by integrating with kinetic systems, utilizing ceramics, polymers, gels, fabrics, metallic components, and composites that can adapt to evolving technology.

In 2010, Schnädelbach examined intelligent facades under three main categories. These are motivation factors, adaptive buildings and components, and design strategies in adaptive architecture. *Motivation factors* are numerous and diverse motivations and driving forces for adaptive design. These motivations can be cultural, social, organizational, and related to communication and social interaction. *Adaptive Buildings and Components* are user and environment. *Design strategies;* mobility, reusability, automation-human intervention, time scales, user focus and stimulus level (Schnädelbach & March, 2010).

In 2011, Ramzy and Fayed proposed two different classification systems. The first of these is to classify kinetic systems in architecture according to system configuration, control techniques and tools. The other is classification based on kinetic systems, control techniques, system configuration, control limit and cost (Ramzy & Fayed, 2011). The movement limit created by the system, known as *kinetism,* varies depending on whether it is partial, inclusive, or a small mobile subunit dependent movement. *Control techniques* deal with how the movement starts, while *system configuration* includes embedded, deployable, and dynamic kinetic structures as determined in Fox and Yeh's (1999) research. *The limit of control* pertains to the degree of environmental changes that the system offers, emphasizing the impact on human comfort and interaction with the building context. Additionally, *cost* is a crucial factor for kinetic fronts, referring to the system's cost relative to its environmental performance (Ramzy & Fayed, 2011).

In 2013, Loonen et al. argued that building envelopes are at the boundary between interior and exterior and are subject to a range of variable conditions, so they must have the ability to react to these changes. The Climate Adaptive Building Shells (CABS) they recommend could repeatedly and reversibly change some of their functions, properties or behaviors over time in response to changing performance requirements and changing boundary conditions, and they do this with the aim of improving overall building performance. Building facades defined as CABS offer the potential to reduce energy demand for lighting and space conditioning by combining the complementary aspects of passive design with active technology. It also positively affects indoor air quality and thermal and visual comfort levels (Loonen et al., 2013). Climate Adaptive Building Shells (CABS) are examined under five main headings according to their characteristics. These include *sources of inspiration*, where nature is a significant influence, with concepts such as tropism, phototropism, and heliotropism inspired by natural adaptability. *Physical interaction* involves building envelopes acting as interfaces for various physical interactions, affecting behaviours like blocking, filtering, and storing energy. *Time scales* refer to temporal solutions generated by environmental influences over the building's life. *Scales of adaptation* indicate characteristic changes on macro or micro levels. *Types of control* highlight the importance of effective control for CABS, with two types of control available.

In 2015, Loonen et al. proposed a new classification, this time examining smart facades under eight headings. These are purpose, responsive function, business, technologies, reaction time, spatial scale, visibility and adaptation scale (Loonen et al., 2015).

In 2015, Kolarevic and Parlac described four activation methods in the building shells. These are engine-based, hydraulic, pneumatic and material-based (Kolarevic & Parlac, 2015). *Engine based systems* consist of motor systems mounted on double skin facades (For example, blinds, sunshades, etc.). These systems can significantly reduce glare and solar heat gain. *Hydraulic* actuators contain a piston placed in a hollow cylinder (Harry, 2016). When force is applied to the piston, a force is applied that moves the objects. The motion thus produced can be linear, rotary, or oscillating. *Pneumatic* facade systems are systems that aim to create movement by pumping air or gas under pressure. It is designed with an understanding that combines the features of biological design and smart technology to create a mobile facade on facades (Harry, 2016). *Material-based* activation systems emerge because of innovations in developing production and control mechanisms. Such materials have multiple applications (Harry, 2016).

In 2018, European COST Action TU1403 'Adaptive Facades Network' proposed a new classification. According to this classification, façade system change is classified based on activation system and triggering event (Bedon et al., 2018). System change occurs as geometrical and rigidity change. Geometric change includes rigid body deformation (rotation and rotation) and non-rigid deformation (bending and expansion) movements under 2 headings.

1. Activation System: It can be realized by self-changing materials, mechanical movements and swelling.

2. Triggering Event: It includes exposure to normal loads, namely its own load, wind-induced vibration, temperature, humidity and daylight events. Other exceptional cases occur because of storm, flood, fire, earthquake and explosion.

The fundamental basis of the classification addressed in this study is the article published by (Heidari Matin & Eydgahi, 2022). In their article, IFS were examined under six headings: passive and active systems. Active technologies are divided into three categories: Mechanical technology, electro-mechanical technology, and information technology. Passive technologies are divided into material-based and passive. The technology that includes these two groups, active and passive technology, is examined under a separate heading known as integrated technology.

Table 1. The chronological order of classification studies on intelligent facade systems

Year	Study	Classification
2000	Fox and Yeh	* Structural innovation *(folding, sliding, expanding, and transforming)* * Material Development *(ceramics, polymers, gels, fabrics, metallic components, and composites)*
2010	Schnädelbach & March	* Motivation Factors *(cultural, social, organizational, and related to communication and social interaction)* * Adaptive buildings and Components *(users, environment)* * Design strategies *(mobility, reusability, automation-human intervention, time scales, user focus and stimulus level)*
2011	Ramzy & Fayed	* Kinetism * Control techniques * System configuration * Limit of control * Cost
2013	Loonen et al	* Sources of Inspiration * Physical Interaction * Time scales * Scales of adaptation * Types of control
2015	Loonen et al	* Purpose * Responsive function * Business technologies * Reaction time * Spatial scale * Visibility * Adaptation scale
2015	Kolarevic & Parlac	* Engine Based * Hydraulics * Pneumatic * Material-Based
2018	European COST Action TU1403	* System Change * Activation System * Triggering Event
2020	Heidari Matin & Eydgahi	* Active technologies *(mechanical technology, electro-mechanical technology, and information technology)* * Passive technologies (*material-based and passive)*

New Classification Proposal

When examining classification studies from the past to the present, it is observed that each study has both different and similar criteria, which is why they have not reached a common point. Therefore, considering the evolving and changing technology, it has been determined that there are numerous systems that activate facade systems. In recent years, material technologies have significantly advanced, and numerous materials capable of creating various effects have been developed. Evaluated within a new framework of classifying intelligent facades based on materials, as proposed by (Addington & Schodek, 2005) in their book. Therefore, within the scope of the study, the materials used in intelligent facades were separated from the technologies and examined under a separate heading. As a result, facades have been

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classified based on the technologies and materials used. The technologies section is divided into five categories: mechanical technologies, electro-mechanical technologies, information technologies, passive technologies, and integrated technologies (Fig 1).

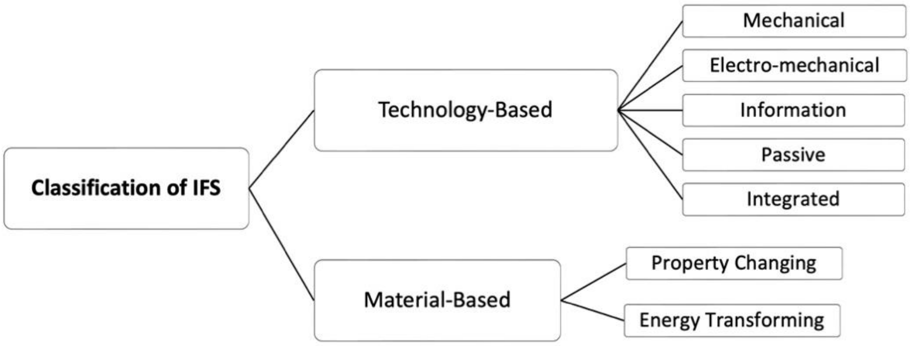

Figure 1. Classification of Intelligent Facade Systems

Mechanical technologies: The first generation of responsive facade systems utilized mechanical technology to improve both the efficiency and comfort of the building (Addington & Schodek, 2005). Although mechanical systems have a relatively long life, non-mechanical parts tend to wear faster (Decker & Zarzycki, 2013). In addition, the maintenance of mechanical components is very difficult and expensive compared to other types of technology applied (Meagher, 2014). Hand-operated façades, which are manually controlled by the occupants, have limited adaptability. Due to the dependence on manpower, mechanical technologies are limited, especially for users with disabilities.

Electro-mechanical technologies: Electro-mechanical technology is recognized as a reliable technology with significant advantages such as standardization of parts, modular design components, cheap initial cost, and centralized monitoring and control (Decker & Zarzycki, 2013). Electro-mechanical sensing, actuation and switching control technologies in buildings were first used in remote-controlled structures located on the facades (Velikov & Thün, 2013).

Information Technologies: Information technology is used in sensitive facades to control interconnected panels via microcontrollers with a distributed control system (Yekutiel & Grobman, 2014). Networks of sensors embedded in responsive façade systems can be connected to software to enable the system not only to collect climate data, but also to exchange data between other building systems, called intermediaries.

Passive Technologies: The first alternative technology is the passive approach to responsive façade design. Based on this design approach, the dependence of a façade system on electrical and manual power has been eliminated and natural resources such as wind, water and sunlight have been used as power sources. The advantages of passive sensitive facades are that they are independent of mechatronic forces, the activation ability provided by environmental variables, and they offer a minimalist approach. On the other hand, these low-cost, low-maintenance and low-tech passive facades do not react in unpredictable conditions due to the uncontrollability of the system.

Integrated Technologies: The mechanical and electro-mechanical components of the façade systems provided an active and sustainable approach to design. However, this primary active approach has been replaced by a passive approach due to the disadvantages of mechanical or electro-mechanical systems. Due to the lack of controllability in passive systems, the integration of passive and active systems with the advantages of both suggests a new system. This integrated technology uses electro-mechanical, information and material-based technology together. In such systems, sensors, actuators, and control systems are all built into the body of advanced materials.

The materials section, on the other hand, is examined under two categories: Property-changing materials and Energy-transforming materials (Fig 1).

Property-changing Materials: Materials that change one of their properties (chemical, mechanical, optical, electrical, magnetic or thermal) in response to a change in ambient conditions and do not need further control.

Energy-transforming Materials: Materials that convert energy from one form to another to achieve the desired end state (Addington & Schodek, 2005).

METHODOLOGY AND METHODS

In this study, a sample of twenty high-rise buildings was selected, comprising ten from Turkiye (Nida Tower Goztepe, Allianz Tower, Istanbul Tower 205, Maslak No:1 Tower, Soyak Crystal Tower, Skyland Office Tower, Zorlu Levent 199, Vakif Bank Headquarters Tower, Palladium Tower, AND Kozyatagı) and ten from various locations worldwide (Torre Reforma, Al Bahar Towers, 1 Bligh Street Tower, Pearl River Tower, NBF Osaki Building, The Leadenhall Building, Salesforce Tower, Doha Tower, PIF Tower, One World Trade Center). In this study, the first constraint is the function of the selected buildings as the focus. To delineate the differences arising from the varied usage characteristics of residential and office buildings, the study has concentrated on office buildings. Office buildings have been preferred due to their significant energy consumption and diverse requirements for optimal indoor environments. The second constraint is the construction year of the case studies. Facade technologies evolve and develop over time. Hence, structures completed within the last 10 years have been chosen to ensure the selection of buildings employing similar technologies. The third constraint of the study is the utilization of intelligent facade technologies in the selected high-rise office case studies. For this purpose, searches have been conducted on web pages using phrases like "smart high-rise building facade" or "intelligent facade systems in high-rise building" to select buildings for which the most information is available (Table 2).

Table 2. Selected case studies of high-rise office buildings from Turkiye and worldwide

Buildings	Year	Location	Height
Nida Tower Goztepe	2013	Goztepe/Istanbul	116 m
Allianz Tower	2014	Atasehir/Istanbul	186 m
Istanbul Tower 205	2019	Levent/Istanbul	220 m
Maslak No:1 Tower	2015	Sariyer/Istanbul	90 m
Soyak Crystal Tower	2014	Levent/Istanbul	169 m
Skyland Office Tower	2017	Sariyer/Istanbul	284 m
Zorlu Levent 199	2014	Levent/Istanbul	170 m
Vakif Bank HQ Tower	2023	Atasehir/Istanbul	221 m
Palladium Tower	2014	Atasehir/Istanbul	180 m
AND Kozyatagı	2015	Kadikoy/Istanbul	110 m
Torre Reforma	2016	Mexico City/Mexico	246 m
Al Bahar Towers	2012	Abu Dhabi/UAE	147 m
1 Bligh Street Building	2011	Sydney/Australia	133 m
Pearl River Tower	2013	Guangzhou/China	309 m
NBF Osaki Building	2011	Osaki/Japan	133 m
The Leadenhall Building	2014	London/England	224 m
Salesforce Tower	2018	San Francisco/USA	326 m
Doha Tower	2012	Doha/Qatar	238 m
PIF Tower	2021	Riyad/Saudi Arabia	385 m
One World Trade Center	2014	New York/USA	541 m

The methodology employed in this study consisted of three distinct stages to ensure a comprehensive analysis and evaluation of IFS in high-rise office buildings.

In the first stage, an extensive review of the international literature was conducted. This involved an in-depth examination of theses, articles, papers, and books related to high-rise office buildings and intelligent facades. The aim was to gather a comprehensive understanding of the existing knowledge and research findings in this field. This literature review served as a foundation for establishing a solid theoretical framework and identifying key concepts and trends in IFSs.

Moving on to the second stage, the focus was on examining the concept of intelligent facades and the various definitions and classifications present in the literature. Previous classification methods were thoroughly reviewed and discussed, providing insight into the different approaches used to categorize and characterize IFSs. Building upon the existing classifications, a classification system was proposed, taking into consideration the unique attributes and functionalities of intelligent facades in high-rise office buildings.

Finally, in the third stage of the study, a comprehensive dataset of high-rise office buildings completed or under construction after the year 2010 was compiled from both Turkiye and around the world. A total of 20 buildings meeting the specified criteria were identified. These buildings were then classified based on the IFS employed, and a detailed table was created to present the findings. A comprehensive evaluation was made by comparing the various smart façade systems used in the sample buildings, and Turkiye's position in the world in terms of smart façade application and innovation in the high-rise office building sector was shed light on. At the end of the study, suggestions for the development of smart façade systems in Turkiye are given.

Through this three-stage methodology, the study aimed to provide a thorough examination and analysis of IFS in high-rise office buildings. The findings and insights gained from this research will contribute to a deeper understanding of the current state and future directions of intelligent facade technologies, both in Turkiye and on a global scale.

CASE STUDIES

Technological advancements in high-rise building facades have gained significant momentum since the year 2000. To examine current technologies and materials, the sample group is limited to buildings constructed within the last 10 years. In this context, facade systems of 20 high-rise buildings, completed in Turkiye and around the world from 2010 onwards, with the highest accessible information, have been analyzed.

Findings on Examined Buildings in Turkiye

Nidakule Göztepe Building is classified as having passive technology due to the combination of aluminium sunshades and passive presence of glass on its façade (Web 1, 2023).

Allianz Tower is categorized as information technology and energy transforming material class due to the presence of displacement ventilation system using electro-mechanical technology, passive technology with low e coated glass curtain wall, the use of LED screens at the top of the structure, and regular advertising broadcasts. Additionally, integrated technology is utilized in this building through the integration of electro-mechanical, passive, and information technologies (Kaplan, et all).

Istanbul Tower 205 incorporates triple silver-coated glass curtain walls and fin-shaped shading elements, placing it in the passive technology class. Additionally, the presence of an electro-mechanical ventilation system with automatic ventilation through mechanically operated louvers, depending on the frequency of user usage, confirms the use of information technology and electro-mechanical technology in the tower. The integration of passive, information, and electro-mechanical technologies is evident in the building (Web 2, 2023).

Maslak No.1 Tower features semi-transparent film-coated facade and mechanical windows for ventilation. Both passive and mechanical technologies are utilized in this structure (Web 3, 2023).

Soyak Crystal Tower is equipped with automated blinds operated by electro-mechanical systems. Passive shading is achieved through double silver-coated glass. Moreover, the presence of automated blinds that adjust the direction of sunlight and respond to climate data, as well as systems that detect carbon levels and provide necessary ventilation, demonstrate the use of information technology in the building. The

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integration of passive, electro-mechanical, and information technologies is also evident in the structure (Akta, 2020).

Skyland incorporates electronic windows, electro-mechanical technology, passive shading glass facade, and information technology-integrated blinds that operate based on climate conditions, demonstrating the use of integrated technology in the building (Web 4, 2023).

The use of LED lighting *in Zorlu Levent 199* Building indicates the use of energy-transforming materials and the presence of fritted glass and horizontal band aluminum sunshades, indicating the use of passive technology (Dörter, 2015).

Vakıfbank Headquarters Tower ensures passive solar control with its glass curtain wall (Web 5, 2023).

Palladium preserves the interior space passively with the use of electro-mechanical facade systems and insulated glass on the exterior, indicating the presence of integrated technology (Web 6, 2023).

AND Kozyatağı features a perforated facade with aluminum sunshades. Additionally, the mention of operable surfaces for fresh air indicates the use of mechanical and passive technology in the building (Web 7, 2023).

When examining the data obtained from the studied buildings, it is observed that the most used intelligent system in the facades of high-rise office buildings in Turkiye is a passive technology. In all buildings, solar control is particularly achieved through passive technology. Integrated technology and electro-mechanical technology follow passive technology. Any facade system that incorporates an active system is classified as an integrated facade system. Electro-mechanical systems are used specifically in windows for natural ventilation and in louvers used for solar control on the facade. Information technology follows passive and electro-mechanical technology, and it is predominantly used in louver systems that learn climate data and user preferences. None of the buildings exhibit the use of shape-changing materials. Energy-changing materials are present in only two structures (Table 3).

Findings on Examined Buildings Worldwide

Torre Reforma Building utilizes a double-layered facade and fixed horizontal sunshades to provide passive control. The presence of windows that automatically open at dawn demonstrates the use of electro-mechanical and information technology in the structure (Miranda and Safarik, 2011).

Al Bahar Towers employ a simple curtain wall facade to passively control solar heat gain. However, the dynamic external sunshades, which move with actuators and simulate the movement of the sun while learning external weather conditions through sensors, fall under the classification of information technology due to their electro-mechanical operation. The integration of these systems confirms the presence of integrated technology in the building (Karanouh and Kerber, 2015).

1 Bligh Street Building is categorized under passive technology due to its high-performance double-skin facade. Louvers, operated by electro-mechanical technology, provide natural ventilation to the structure. These louvers also utilize sensor data such as rain and temperature for their operation, incorporating information technology (Web 8, 2023). The presence of photovoltaic solar panels indicates the use of energy-transforming materials. Moreover, the integration of passive and active systems confirms the existence of integrated technology in the building (Web 9, 2023).

Pearl River Tower indicates the use of passive technology using fritted glass. Additionally, the presence of automated louvers controlled by climate control systems in the building demonstrates the utilization of information and electro-mechanical technology. The integration of solar panels into the structure signifies the presence of energy-transforming materials in the building's facade. Thus, the building also falls under the category of integrated technology (Tomlinson et al., 2014).

NBF Osaki Building utilizes electro-mechanical systems on the facade to circulate water. The presence of solar panels powering this system indicates the use of energy-transforming materials in the building. The building, which possesses integrated technology, also achieves passive cooling through the evaporation of water based on ambient temperature, thereby cooling the interior and surrounding environment (Yamanashi et all, 2011).

The Leadenhall Building features a double-layered transparent glass facade for passive solar control. Additionally, motorized louvers connected to an electro-mechanical system prevent unwanted heat gains in the building. The combination of passive and electro-mechanical systems classifies the building under integrated technology (Young et all, 2013).

Salesforce Tower achieves passive shading through a transparent glass metal sunshade on a mother-of-pearl surface. LED screens installed on the lower six floors of the building display environmental data. This indicates the presence of both energy-transforming materials and information technologies in the building. Additionally, the facade-integrated ventilation system provides electro-mechanical ventilation. The combination of passive and active systems classifies the building under integrated technology (Web 10, 2023).

Doha Tower is classified as passive and electro-mechanical due to its double-skin facade and layers composed of aluminum components. The presence of both passive and electro-mechanical systems highlights the existence of integrated technologies (Web 11, 2023).

PIF Tower is classified under the headings of passive triple-insulated curtain wall and adjustable glass fins, indicating the use of information and electro-mechanical technologies. In addition to these integrated technologies, the presence of photovoltaics signifies the use of energy-transforming materials in the building (Soto and Al-Shihabi, 2015).

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One World Trade Center Building achieves passive solar control through its glass curtain wall that contains only low iron content (Web 12, 2023).

When examining the data obtained from the investigated structures, it is observed that the most used intelligent system in the facades of high-rise office buildings worldwide is passive technology. Like Turkiye, all buildings have employed passive technology, particularly for solar control. Passive technology is followed by integrated technology and electro-mechanical technology, which are present in 9 structures. Electro-mechanical systems are used in shading devices attached to the facade and in shading elements integrated into the building envelope to achieve solar control. Information technology, on the other hand, follows electro-mechanical and integrated technology, and it is found in 6 structures. This technology is primarily used in LED displays and for learning external weather conditions through sensors to optimize building performance. Unlike in Turkiye, the use of photovoltaics, which is an energy-changing material, is frequently encountered in the investigated structures worldwide. Photovoltaics are employed to provide the required energy for the operation of electro-mechanical components that require movement in the facade. Lastly, like Turkiye, none of the buildings exhibit the use of materials that can change their properties (Tablo 3).

Table 3. Findings on Examined Buildings in world and Turkiye

	BUILDINGS	Technology-based					Material-based	
		Mechanical	Electro-Mechanical	Passive	Information	Integrated	Property-Changing	Energy-Transforming
WORLD	Torre Reforma		✓	✓	✓	✓		
	Al Bahar Towers		✓	✓	✓	✓		
	1 Bligh Street Building		✓	✓	✓	✓		✓
	Pearl River Tower		✓	✓	✓	✓		✓
	NBS Osaki Building		✓	✓		✓		✓
	The Leadenhall Building		✓	✓		✓		
	Salesforce Tower		✓	✓	✓	✓		✓
	Doha Tower		✓	✓		✓		
	PIF Tower		✓	✓	✓	✓		✓
	One World Trade Center			✓				
TURKIYE	Nida Tower Goztepe			✓				
	Allianz Tower		✓	✓	✓	✓		✓
	Istanbul Tower 205		✓	✓	✓	✓		
	Maslak No:1 Tower	✓		✓				
	Soyak Crystal Tower		✓	✓	✓	✓		
	Skyland Office Tower		✓	✓	✓	✓		
	Zorlu Levent 199			✓				✓
	Vakif Bank HQ Tower			✓				
	Palladium Tower		✓	✓		✓		
	AND Kozyatagı	✓		✓				

CONCLUSION AND RECOMMENDATIONS

High-rise buildings have experienced significant advancements due to progress in material technology since their inception. Particularly, revolutionary changes in facade design occurred with the development of new materials and construction techniques following the industrial revolution. In the 1970s, there was a paradigm shift in facade design. The need to improve energy efficiency and indoor comfort conditions led to the emergence of facades aimed at reducing energy consumption and enhancing user well-being. It was during this transformative period that the concept of intelligent facades emerged. Considering that the concept of intelligent facades continues to evolve, it is evident that there is currently no standardized terminology or classification system. However, to comprehensively examine and understand IFSs, it is crucial to delve deep into the underlying mechanisms triggering facade transformations. To facilitate this understanding, a classification framework considering the use of materials and the complexity of devices integrated within these facades is necessary. In the context of this study, changes brought about by integrated devices and mechanisms are categorized into five groups: passive, mechanical, electro-mechanical, integrated technology, and information technology, while changes stemming from materials are classified under energy and property-transforming materials.

Based on the newly created classification, a comprehensive analysis of a total of 20 buildings selected from Turkiye and worldwide reveals that the predominant system used is passive technology. Passive technology, which harnesses energy from natural sources, emerges as the preferred choice due to its ecological and economic advantages. Following passive technology, the second most used system is integrated technology. This is because any active technology system added to systems that derive energy from nature and humans, such as passive and mechanical technology, falls into the category of integrated technology and operates in hybrid mode. The third preferred technology is electro-mechanical technology. The use of electro-mechanical technology has increased, especially in windows and blinds, which are important elements of the facade, allowing for remote control. Among all technologies, information technology, which is the latest and still rapidly developing technology, ranks fourth. When examining the materials used in buildings, only energy-changing materials such as photovoltaics and LED displays have been found. Mechanical technology is present in only two of the buildings examined in Turkiye. Although no materials with changing properties have been found in any of the investigated structures, they are used in facade applications in architecture. As a result of all the investigations, it can be said that energy-changing materials are used in more buildings worldwide than in Turkiye, but there is still parallel development in facade technology.

Analysis of facade systems in Turkiye reveals the prevalence of passive, integrated, and electro-mechanical facade technologies, indicating the increasing adoption of energy-efficient and technologically advanced solutions. However, there are still opportunities for further development and improvement in intelligent facade applications in Turkiye.

The following recommendations can be considered to increase the development of intelligent facades in Turkiye:

- Encouraging research and development efforts focused on intelligent facade technologies, materials, and systems specifically tailored to the climate, building regulations, and user requirements in Turkiye. This can facilitate the creation of innovative solutions that optimize energy performance, indoor comfort, and user experience.
- Promoting knowledge and expertise exchange among experts, including architects, engineers, manufacturers, and researchers. Industry-academia collaborations can be emphasized in this regard. Fiscal incentives, tax benefits, and building certification programs can encourage building owners and developers to invest in energy-efficient and intelligent facade technologies.
- Increasing awareness among architects, engineers, investors, and users about the benefits and potential of IFSs. Educational programs, workshops, and conferences can be encouraged to train professionals in the design, installation, and maintenance of IFSs, emphasizing their impact on energy conservation and environmental sustainability.

By implementing these recommendations, Turkiye can further contribute to the advancement of intelligent facade development, thereby supporting energy efficiency goals, sustainable building practices, and improved user experiences in high-rise office buildings and beyond.

This study provides an evaluation of intelligent facade systems in selected buildings from Turkiye and various regions worldwide. However, factors such as climatic region and budget were not considered in this analysis. Nonetheless, future studies could explore how the facades of high-rise office buildings may evolve by incorporating one or more of these criteria. Furthermore, by maintaining the same classification framework and examining more high-rise building examples tailored to different user profiles, a comparison can be made to highlight the differences between the facades of high-rise office buildings and those of other types of high-rise structures.

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Resume

Fazilet TUĞRUL OKBAZ completed her undergraduate education with honors in the Department of Architecture at DEU in 2012. She has completed her master and PhD studies at Mimar Sinan Fine Arts University. She started as a research assistant at Gebze Technical University in 2013 and has been serving as an Instructor, PhD. since 2020. Her research areas include high-rise buildings, building technologies, and intelligent facades. She has published many national and international scientific paper and book chapters. She contributes building science, structural systems and technologies, tall buildings courses, and design studios.

Simay AYDİNÇ, received her bachelor's degree from Gebze Technical University, department of Architecture in 2020 and her master's degree in architecture in 2023 from Gebze Technical University. She currently works as a project coordinator at Aterko Construction. Her primary research interests are high-rise buildings, high-rise building facades and facade technologies.

Ferhat PAKDAMAR is an Associated Professor of the Department of Architecture at İstanbul Technical University since 2024. He has completed his master and PhD studies at Istanbul Technical University. He worked as an academic and served as the vice dean of the Gebze Technical University Faculty of Architecture. His research interests are artificial intelligence and performance analysis of structures in his PhD thesis. He has published many national and *international scientific paper and book chapters. He contributes structural courses, design studios and also conducts some graduate thesis.*