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A new classification proposal for adaptive façades with hybrid technology

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Abstract

In the study, a classification approach is proposed to characterize and increase the legibility of the adaptive facades with hybrid technology that can be obtained by integrating smart materials into active adaptive facade systems. In this context, firstly, classification studies, adaptive element prototypes and applications were examined. Then, the classification approach was categorized as smart material properties, smart system properties and purposes. It was predicted that the purposes will develop and diversify depending on the properties of smart materials and systems. Based on this prediction, a classification diagram was developed in which the purposes are located at the intersection. In this diagram, smart material and system properties are combined by orienting towards the purposes. It is critical that new material and system properties that will be discovered in the coming years be added to the diagram. Therefore, in the diagram, each category was composed of cells that develop radially from the center outwards. In the evaluation, case studies were analyzed and the usage intensity of the characteristics was determined. This situation was also visualized through the diagram. As a result, the legibility of adaptive facades has increased and its characterization has become easier, thanks to the prominent characteristics.

Highlights

- Explaining the properties of smart material and system used in adaptive facades and determining facade performance purposes.
- Developing a classification diagram for hybrid adaptive facade systems.
- Characterization of the design and application parameters of adaptive facades, facilitating the analysis of these facades and increasing its understandability.

Keywords

Adaptive facade; Classification proposal; Smart material; Smart system; Hybrid technology

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Hibrid teknolojili adaptif cepheler için yeni bir sınıflandırma önerisi

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Anahtar Sözcükler

Adaptif cephe; Sınıflandırma önerisi; Akıllı malzeme; Akıllı sistem; Hibrid teknoloji

Öz

Çalışmada, aktif adaptif cephe sistemlerine akıllı malzemelerin entegrasyonuyla elde edilen hibrid teknolojili adaptif cephelerin okunaklılığını artırmak ve karakterizasyonu için bir sınıflandırma yaklaşımı önerilmektedir. Bu bağlamda öncelikle sınıflandırma çalışmaları, adaptif eleman prototipleri ve uygulamaları incelenmiştir. Ardından sınıflandırma yaklaşımı akıllı malzeme özellikleri, sistem özellikleri ve amaçlar olmak üzere kategorize edilmiştir. Amaçların akıllı malzeme ve sistem özelliklerine bağlı olarak gelişip çeşitleneceği öngörülmüştür. Bu öngörüye dayanarak amaçların kesişimde konumlandırıldığı bir sınıflandırma diyagramı geliştirilmiştir. Bu diyagramda akıllı malzeme ve sistem özellikleri amaçlara doğru yönlenerek birleşmektedir. Gelecek yıllarda keşfedilecek yeni malzeme ve sistem özelliklerinin diyagrama eklenmesi kritik önem taşımaktadır. Bu sebeple diyagramda, her bir kategori merkezden dışa doğru ışınsal biçimde gelişen hücrelerden oluşturulmuştur. Değerlendirmede örnek çalışmalar analiz edilerek karakteristiklerin kullanım yoğunluğu belirlenmiştir. Bu durum diyagram aracılığıyla da görselleştirilmiştir. Sonuç olarak, öne çıkan karakteristikler sayesinde adaptif cephelerin okunaklılığı artmış ve karakterizasyonu kolaylaşmıştır.

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Öne Çıkanlar

- Adaptif cephelerde kullanılan akıllı malzeme ve sistem özelliklerinin açıklanması ve cephe performans hedeflerinin belirlenmesi.
- Hibrid adaptif cephe sistemleri için sınıflandırma diyagramı geliştirilmesi.
- Adaptif cephelerin tasarım ve uygulama parametrelerinin karakterizasyonu, bu cephelerin analizinin kolaylaştırılması ve anlaşılırlığının arttırılması.

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INTRODUCTION

The issue of energy efficiency of the building and indoor user comfort, which is one of today's problems, requires the construction of buildings with high environmental performance. In order to fulfill this requirement, building shells that interact with the physical environment come to mind. Surface area of building facades is large, so the building facades come into prominence more than the roof. Preventions to be taken against the physical environment on the facades will reduce the energy consumption of the building for heating, cooling and lighting. Therefore, it will contribute to the energy efficiency of the building. At the same time, it will have a direct positive impact on the health of the users by providing optimum thermal and visual comfort conditions in the building interiors (Scıuto, 1998; Herzog et al., 2004; Loonen et al., 2015; Aelenei et al., 2016; Attia et al., 2018; Hraska, 2018; Matin & Eydgahi, 2019; Böke et al., 2022; Voigt et al., 2022). Additionally, the human who is the user of the building is dynamic in this cycle. Therefore, transition from static to dynamic of building facades is necessary (Pask, 1969). For this reason, Pask (1969) stated that what the building will learn and how it will adapt to the dynamic natural environment and people should be explained in the architectural design process. In the context of these issues, one of the promising approaches is to consider adaptive solutions on the facades to both optimize the energy efficiency of the building and increase interior user comfort (Loonen et al., 2013; Loonen et al., 2015; Aelenei et al., 2016; Matin & Eydgahi, 2019; Böke et al., 2022; Voigt et al., 2023).

Developments in the designs and applications of adaptive facades continue in parallel with the developments in computer science, electrical control system, artificial intelligent, cybernetics and material science (Matin & Eydgahi, 2019). Adaptive facades, which have few applied examples, are mostly in the prototyping stage. This clearly shows that adaptive facade applications are a complex task. This task that has multi-criteria requires considering many problems simultaneously. In the context of varying environmental factors and interior user requirements, these facades must be able to respond to many scenarios. For this reason, design and application parameters should be detailed with the aim of ensuring energy efficiency and improving indoor comfort conditions while benefiting from climatic data (Loonen et al., 2015; Aelenei et al., 2016; Nady, 2017). Defining and characterizing of the design and application parameters of adaptive facades is important in terms of facilitating the analysis of these facades and increasing their understandability.

At the stage reached with today's technology, adaptive facades don't provide adaptation only through the system or only through the material. Facade systems that take advantage of both material and system properties are also developed. The main purpose of the study is to characterize of hybrid facade technologies obtained by the integration of smart materials into active adaptive smart facade systems and to propose a classification approach to increase their legibility and to reveal of the potential of using of classification criteria. In this context, firstly existing classification approaches are examined. Then, adaptive facade case studies are analyzed within the scope of smart system and material properties and the performance aims of the facade. Thus, the techniques, technologies, systems and materials used in adaptive building facades will be described, their advantages and disadvantages will be discussed, and solution methods and suggestions will be evaluated. A classification diagram will be developed by categorizing the properties to characterize adaptive facades with hybrid technology. It is aimed that the properties of adaptive facade with hybrid technology are legible on the diagram. Additionally, in order to use the classification approach effectively in applications, the usage potential of the classification characteristics will be revealed by using case studies. Thus, it is aimed to facilitate the legibility and development of adaptive facades with hybrid technology.

RESEARCH METHODOLOGY

In the study, a classification approach is proposed to characterize and increase the legibility of adaptive facades with hybrid technology and an evaluation is carried out through case studies to determine the usage potential of the classification characteristics. In this context, the method followed in the study is summarized as follows (Figure 1).

1. ***Preparation:*** Literature review on existing classification studies, adaptive facade element prototypes and applications.
2. ***Processing:*** Categorization of adaptive facades with hybrid technology into smart material and system related properties and facade performance related purposes. Detailing of the each category with the determined characteristics and explaining of the characteristics with samples.
3. ***Proposal:*** Development of a classification diagram to visualize the characteristics determined for adaptive facades with hybrid technology.
4. ***Evaluation:*** Carrying out an evaluation through case studies, using the diagram developed to determine the usage potential of the characteristics determined for adaptive facades with hybrid technology. Thanks to this diagram, it is aimed to facilitate of the perception of the prominent characteristics for adaptive facades with hybrid technology and thus to characterize of these facades.

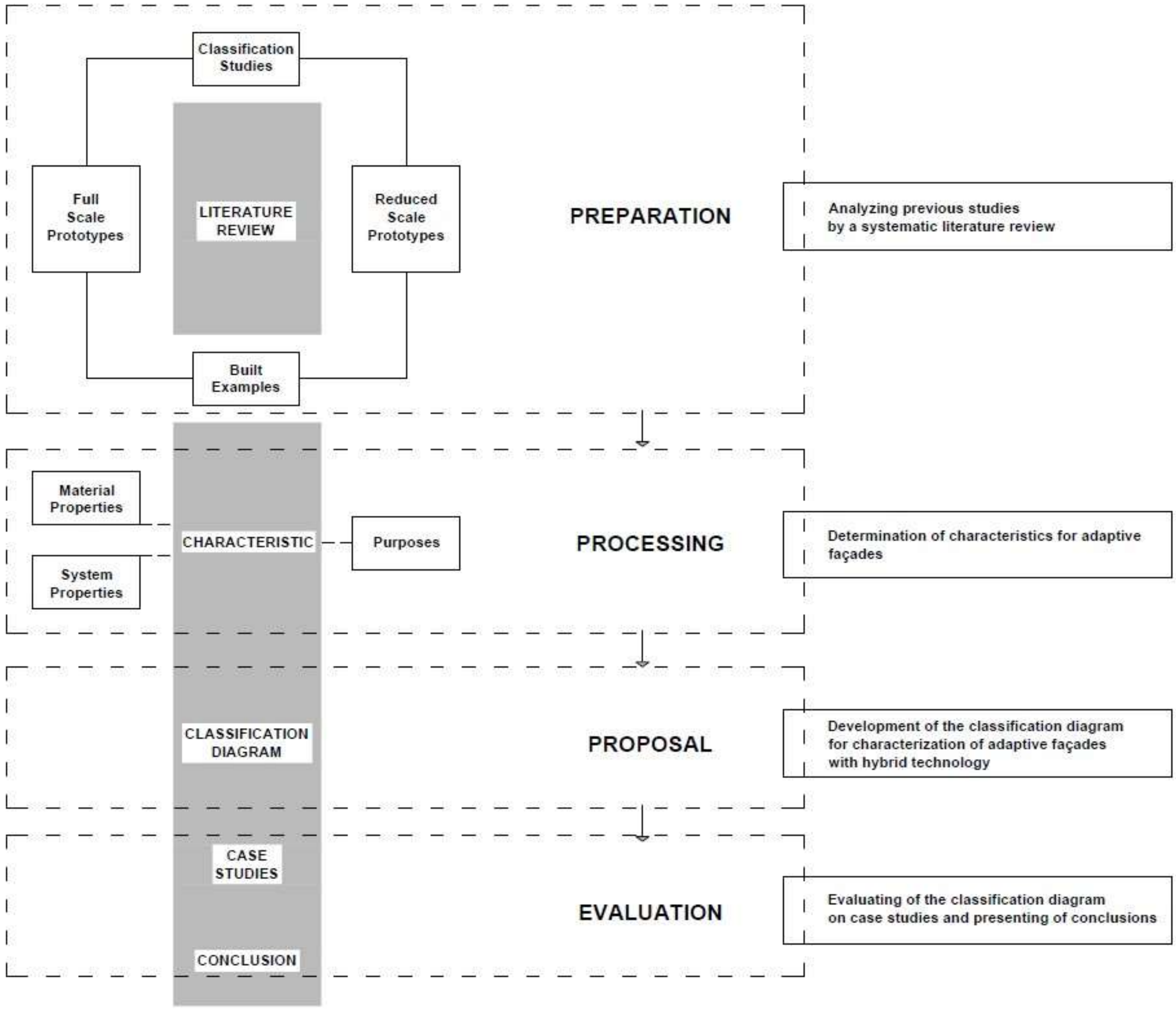


Figure 1. Research methodology of the article.

OVERVIEW OF PREVIOUS STUDIES

In the literature, there are various classification approaches, adaptive element prototypes and applications developed by researchers with different approaches for adaptive facades. In order to propose a new classification approach, previous classification approaches and adaptive element designs must be analyzed. In this context, classification studies, research projects and applications have been comprehensively examined to characterize the properties of adaptive facades. In these reviewed studies, the prominent concepts in the context of classification were identified and headings were determined for Table 1. As seen in Table 1, the concepts were organized into two categories, smart material properties and smart system properties, depending on the material or system-based operation of adaptive facades. In addition, a separate category was created as purposes, depending on the performance objectives of adaptive facades. Some of the classification studies are explained as follows and summarized as seen in Table 1. The analyzes of the case studies evaluated within the scope of the study are summarized in Table 4 in the 'analysis of case studies' section of the study.

Sherbini & Krawczyk (2004) emphasized to the importance of perceiving, processing and analyzing information in an smart system and reacting with various control mechanisms in a timely or within the period. In addition, it was predicted in the study that such systems should have the learning ability.

Addington & Schodek (2005) classified smart materials with potential for use in adaptive systems as property changing material and energy exchanging material. In the study, the properties of the systems including sensors, detectors, transducers, actuators and microprocessors were also explained, and the applicability of smart materials as a technology such as these systems was predicted due to its naturally occurring active behavior.

Loonen et al. (2013) classified adaptive facades in the context of performance purposes, time-scales of motion, scales of adaptation and motion control types. Based on the case studies examined, adaptive facade purposes were determined as thermal comfort, visual comfort, air flow and electrical efficiency (production or consumption). It was possible to increase the possibilities through the interactions of these four main purposes and fifteen different possible performance combinations were created for adaptive facades. The adaptation time of adaptive facades is categorized as seconds, minutes, hours, diurnal and seasons based on case studies. The adaptation scale is categorized as 'macro' scale for situations such as shape change and 'micro' scale for situations such as optical property change. Within the scope of motion control types, a classification has been proposed as 'extrinsic control' based on case studies with high-tech automation systems and 'intrinsic control' based on case studies based on the smartness of components such as materials.

Altın & Orhon (2014) discussed adaptive facades with smart properties in adapting to physical environment and evaluated these facades in terms of the functions of the facade in the context of sustainability. According to the classification made in the study, smart building facades that producing energy, balancing heat loss and/or gain, cleaning itself and/or the air and serving other functions were examined. Within the scope of other functions, a media facade was discussed and it was emphasized that these examples could be developed and diversified for the future.

Loonen et al. (2015) followed a method to classify adaptive facades by explaining the concepts of these facades. In the study, eight basic concepts were defined by analyzing previous classification approaches. These concepts are goal/purpose, responsive function, operation, technologies (materials & systems), response time, spatial scale, visibility, degree of adaptability. These concepts were further detailed with sub-concepts and a new classification was proposed. Loonen et al. (2015) didn't detail on the concept of technologies (materials & systems) but stated it as an important item that should be emphasized in future studies.

Aelenei et al. (2016) proposed an approach to the characterization of concepts for adaptive building shells. It was predicted that thermal and visual comfort have a great impact on ensuring user comfort conditions and energy efficiency and should be considered as priority criteria.

Altın & Orhon (2016) classified adaptive facades as system-based and material-based according to the method this facade respond to environmental factors and examined system-based adaptive facade case studies in terms of energy conservation. In the case studies examined, it was seen that adaptive facades improved indoor comfort conditions and minimized the energy need of the building.

Orhon (2016a) evaluated adaptive building shells in terms of motion control technology. In this context, adaptive behavior has been examined as system and material-based technology. In technology that works based on system properties, sensors are used to perceive environmental factors and the operation of the system are carried out through mechanical, electrical-based, electro-mechanical, hydraulic and pneumatic actuators. In technology based on material properties, the perception of environmental factors and the control of the system are achieved passively, thanks to the properties of the material (Orhon, 2016a).

Loonen et al. (2017) compiled the current status of adaptive facades for building performance simulations. In this context, adaptive facades were analyzed in terms of perception, control mechanism and achievement of performance purposes.

Yoon (2018) classified thermo-responsive facade component design strategies. In the study, while type of material, type of stimuli, typology of behavior, scales of adaptation and method of integration criteria stand out for the design process, it is seen that actuators provide energy support to the system in material-based systems.

Matin & Eydgahi (2019) analyzed the control technologies used in adaptive facades and proposed a classification based on control, perception, actuation, material and structural technologies. In this classification, technologies are explained under 5 categories: mechanical, electromechanical, passive, information and advanced material technology.

Böke et al. (2020) aimed to clarify the necessary conditions for the realization of automation in facade applications and to determine the level of development of adaptive facade automation. In this context, analysis of case studies was carried out to determine which automatic adaptive functions were applied on the facades. The realization of adaptive functions on the facade was evaluated through adaptive criteria. According to this evaluation, it is predicted that the current level of automation development in facade applications doesn’t yet correspond to cyber-physical systems such as industry 4.0.

Böke et al. (2022) discussed adaptive facades as active and passive adaptation approaches, as classified in the study of Loonen (2013). The use of high-tech complex automation technologies and digital control in the active adaptation strategy and the use of smart properties of materials in the passive adaptation strategy (Hensel, 2013, as cited in Böke et al., 2022; Loonen, 2013) were combined to determine the possibility of implementation of the hybrid adaptation strategy. It was predicted that cyber-physical systems provide high performance to enable multifunctional solutions on hybrid facades. It was also emphasized that more research should be carried out for the implementation of hybrid technology facades.

Voigt et al. (2022) aimed to identify and define the basic characteristics that are important for adaptive facades. This study, in which some characteristics specific to adaptive facades are explained, constitutes an important reference that can be used in classification studies. In the study control system, goal of the adaptation, sensor input, type of adaptation, type of actuation, trigger event, size of the adaptive element, user override permission, visibility of the adaptation, adaptive function, performance impact, position of adaptive element, connection to HVAC, integration of adaptive element, reaction/adaptation time, degree of adaptive reaction were discussed.

Voigt et al. (2023) proposed a classification approach for adaptive facades. Classification parameters determined as control system, goal of the adaptation, sensor input, type of adaptation, type of actuation, trigger event, size of the adaptive element, user override permission, visibility of the adaptation, adaptive function, position of adaptive element, connection to HVAC, integration of adaptive element, reaction/adaptation time, degree of adaptive reaction were discussed. Some of the design parameters discussed in the study are similar to each other and are too detailed. It is predicted that this situation may create confusion in the definition of adaptive facades.

Table 1. Determination of characteristics for adaptive facades with hybrid technology

Properties / Classification Studies	Smart System Properties								Smart Material Properties								Purposes						
	Working Principle	Type of Stimuli	Typology of Motion	Scales of Adaptation	Sensor Input	Reaction Time	Learning Ability	Type of Actuation	Type of Material	Type of Stimuli	Typology of Behavior	Scales of Adaptation	Position of Material	Reaction Time	Learning Ability	Power Supply Support	Thermal Comfort	Visual Comfort	Indoor Air Quality	Shading Effect	Energy Generation	Media Influence	Personal Control
Sherbini & Krawczyk (2004)	✓	✓			✓	✓	✓	✓									✓	✓		✓			✓
Addington & Schodek (2005)	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓		✓		✓	✓		✓	✓		
Loonen et al. (2013)	✓			✓	✓	✓			✓	✓							✓	✓	✓		✓		
Altın & Orhon (2014)																	✓	✓		✓	✓	✓	
Loonen et al. (2015)	✓	✓	✓	✓		✓			✓				✓				✓	✓	✓	✓	✓		✓
Aelenei et al. (2016)	✓	✓		✓		✓			✓	✓		✓					✓	✓	✓	✓	✓		
Altın & Orhon (2016)	✓	✓	✓	✓	✓												✓	✓	✓	✓	✓	✓	✓
Orhon (2016a)	✓	✓			✓	✓		✓	✓	✓	✓						✓	✓	✓	✓	✓	✓	✓
Loonen et al. (2017)	✓	✓			✓			✓	✓	✓			✓				✓	✓	✓	✓			✓
Yoon (2018)	✓		✓	✓					✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓			✓
Matin & Eydgahi (2019)	✓	✓			✓	✓	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓			✓		✓
Böke et al. (2020)	✓	✓			✓	✓		✓					✓				✓	✓	✓	✓	✓		✓
Böke et al. (2022)	✓	✓			✓		✓	✓	✓	✓	✓				✓	✓	✓	✓	✓	✓	✓		✓
Voigt et al. (2022)	✓	✓		✓	✓	✓		✓	✓				✓										✓
Voigt et al. (2023)	✓	✓	✓	✓	✓	✓		✓					✓				✓	✓	✓		✓		✓

Before a new classification approach is proposed, the characteristics obtained through literature review will be explained under the categories of smart system and smart material properties and purposes. Then, a diagram will be developed to make the classification approach more understandable.

Smart system properties

Adaptive facades are generally classified in the literature as extrinsic or active and intrinsic or passive in terms of **working principle** (Loonen et al., 2013; Loonen et al., 2015; Aelenei et al., 2016; Orhon, 2016a; Böke et al., 2020; Böke et al., 2022). Sensors, processors and actuators are generally involved in the extrinsic or active adaptation process (Sherbini &Krawczyk, 2004; Addington&Schodek, 2005; Loonen et al., 2013; Loonen et al., 2015; Matin & Eydgahi, 2019; Böke et al., 2020; Böke et al., 2022). In the intrinsic or passive adaptation process, the adaptability of smart materials is generally used (Addington&Schodek, 2005; Yoon, 2018; Matin & Eydgahi, 2019; Böke et al., 2022), (Table 2). The main purpose of a material-based adaptive facade is the zero-energy operation of the facade system.

Type of stimuli diversifies as indoor physical conditions and external atmospheric factors (Aelenei et al., 2016). These factors are exemplified as seen in Table 2. In a system-based adaptive facade, stimuli are generally perceived through sensors.

Typology of motion on an adaptive facade can diversify according to purpose of façade and working principle of system. As seen in Table 2, motion typologies of the facade or element are exemplified.

In adaptive facade systems, the adaptation behavior of the elements diversifies the **scales of adaptation**. These adaptation behaviors are classified as macro and micro scale (Loonen et al., 2013; Hraska, 2018). Macro-scale motion is based on changing the properties of the facade elements such as form, size and location. Micro-scale motion is based on changes in the optical and thermophysical properties of the facade elements (Addington&Schodek, 2005; Loonen et al., 2013; Hraska, 2018; Yoon, 2018). Scales of adaptation is expressed as visibility of the adaptation in some studies (Loonen et al., 2015; Aelenei et al., 2016; Voigt et al., 2022; Voigt et al., 2023), (Table 2).

Sensor input can be diversified as adaptive facade components that perceive, measure and convert into digital signals of stimuli (Sherbini &Krawczyk, 2004; Tashakori, 2014; Loonen et al., 2017). Loonen et al., (2017) detailed the sensors by categorizing as climate boundary conditions, room/material states and occupant preference. As seen in Table 2, sensor types are exemplified according to the stimulus. Sensors are mostly used in active adaptive facades but material can work as sensor in systems where smart materials are used.

Reaction time (time scales) is a concept that expresses the response time to various environmental effects. As exemplified in Tables 2, adaptive facades can respond to environmental effects at different time scales (Sherbini &Krawczyk, 2004; Loonen et al., 2013; Loonen et al., 2015; Böke et al., 2020; Voigt et al., 2022; Voigt et al., 2023).

Learning ability is a concept related to updating the system with different methods when new information is received in a system (Sherbini &Krawczyk, 2004). In adaptive systems, programmed (hourly, etc.) and machine learning can be examples of this situation. In smart materials, memory ability can be given as an example (Sherbini &Krawczyk, 2004; Addington&Schodek, 2005; Matin & Eydgahi, 2019; Böke et al., 2022).

Type of actuation is a concept used for actuation systems on active adaptive facades. In the literature, the usage of mechanical, electrical-based, electro-mechanical, hydraulic and pneumatic actuators is common and the applications of these actuators are carried out (Addington & Schodek, 2005; Orhon, 2016a; Matin & Eydgahi, 2019; Böke et al., 2020), (Table 2).

Table 2. Description and sampling of smart system properties

Smart System Properties	**Working Principle**	Active Technology	Sensors, Processors and Actuators
		Passive Technology	Material Based Technology
	Type of Stimuli	Temperature, Light/Solar Radiation, Glare, Humidity, Air Quality, Wind Speed, Occupant/User, Pre-programmed, Electricity, Magnetic fields, Multiple stimuli	
	Typology of Motion	Opening, Closing, Displacement, Rotation, Deployment, Retraction, Inflation, Folding, Bending/Twisting, Color change, Transparency	
	Scales of Adaptation	Macro scale	Change of shape, size, location such as properties
		Micro scale	Change of phase, optical, thermophysical such as properties
	Sensor Input	Temperature, Light, Humidity, Air, Wind, Electricity, Magnetic field, Motion	
	Reaction Time (Time Scales)	Seconds, Minutes, Hours, Diurnal, Seasons, Years	
	Learning Ability	Programmed (hourly etc.), Machine learning	
	Type of Actuation	Mechanical, Electrical, Electro-mechanical, Pneumatic, Hydraulic	

Smart material properties

In the study of (Addington & Schodek, 2005), the classification made for smart materials in terms of the **type of material** was taken into consideration and smart materials were examined in two separate groups: materials that change properties and materials that convert energy. Within the scope of the study, materials that change shape, phase and optical properties as materials that change property, and photovoltaic cells as materials that convert energy are examined.

Type of stimuli diversifies as indoor physical conditions and external atmospheric factors (Aelenei et al., 2016). These factors are exemplified as seen in Table 3. In a material-based adaptive facade, stimuli are generally perceived through smart materials. Therefore, the smart material acts as a sensor.

The concept of **typology of behavior** states to the behavior of smart materials in material-based systems. This concept has a similar meaning to the concept of typology of motion, which is explained for active adaptive facades.

In material-based adaptive facade systems, the **scale of adaptation** varies according to the smart material's response to the stimulus. As seen in Table 3, some smart materials behave on a macro scale, while others change on a micro scale.

Position of material states the location of smart materials in the system. In this study, it is characterized as external, in between and internal, as seen in Table 3.

As exemplified in Table 3, the **reaction time (time scales)** in material-based adaptive facades varies depending on the properties of the smart material.

Table 3. Description and sampling of smart material properties

Smart Material Properties	**Type of Material**	Property changing	Change of shape (thermobi-metals, shape memory alloys, shape memory polymers, electroactive polymers etc.)
			Change of phase (paraffine, salt hyrate etc.)
			Change of optical properties (chromics, etc.)
		Energy exchanging	Generate of energy (photovoltaics, etc.)
	Type of Stimuli	Temperature, Light/Solar Radiation, Glare, Humidity, Air Quality, Wind Speed, Occupant/User, Pre-programmed, Electricity, Magnetic fields, Chemical substances, Multiple stimuli	
	Typology of Behavior	Opening, Closing, Energy conversion, Rotation, Deployment, Contraction, Elongation, Inflation, Folding, Bending/Twisting, Color change, Transparency	
	Scales of Adaptation	Macro scale	Change of shape, size, location such as properties
		Micro scale	Change of optical, thermophysical such as properties
	Position of Material	External	
		In between	
		Internal	
	Reaction Time (Time Scales)	Seconds, Minutes, Hours, Diurnal, Seasons, Years	
	Learning Ability	Memory ability	
	Power Supply Support	Electricity (DC, servo and stepper motors), Mechanical force, Heat source (hot air gun), Air pressure (pneumatic source)	

Learning ability is a concept related to the memory ability of smart materials in material-based operating systems. An example of this situation is the shape change of smart materials under the effect of a stimulus and the return to the original shape when the stimulus effect ends.

Power supply support states the energy provided externally for the activation of the material in material-based systems. In some cases, material properties may be insufficient to react to stimuli or the reaction time of the material may be long. Power supply supports commonly used for activation of the material in these cases are exemplified in Table 3.

Purposes

Thermal comfort is a concept related to ensuring the thermal energy balance of the building. (Loonen et al., 2013). **Visual comfort** is one of the important purposes that can be achieved by providing sufficient daylight to the interior and reducing glare in the space (Loonen et al., 2013; Altın & Orhon, 2014), which directly affects the physiological and psychological health of the user. As a result of analyzing the information received from users or sensors, indoor thermal and visual comfort level can be achieved through various smart materials and systems (Addington&Schodek, 2005; Loonen et al., 2013; Loonen et al., 2015; Yoon, 2018; Böke et al., 2020; Voigt et al., 2023). Regarding this issue, Altın & Orhon (2014) explained the effect of such facades on visual comfort by giving examples of facades that balance building heat losses and gains through shading elements, Sherbini Krawczyk (2004) emphasized the concepts of time consideration and learning ability as smart criteria to achieve purposes such as thermal and visual comfort.

Indoor air quality is a concept related to the behavior of the adaptive facade according to the direction and speed of the wind and the intake of sufficient fresh air into the space (Loonen et al., 2013; Loonen et al., 2015). In addition, controlling ventilation behavior depending on seasonal requirements can support the heating-cooling balance of the space (Böke et al., 2022) and the building performance in terms of energy consumption (Orhon, 2016a). In some cases, the ventilation purpose can be provided manually instead of being a part of the adaptive control mechanism in adaptive facades (Böke et al., 2020).

Shading effect is a concept that affects the visual and thermal comfort level of the interior and the energy consumption of the building for heating and cooling purposes (Loonen et al., 2015; Altın & Orhon, 2016). It can be said that the thermal and visual comfort level and energy consumption level achieved for the space can determine the success criteria of an adaptive shading element design.

Energy generation is an important purpose that allows adaptive facades to be self-sufficient, rather than being dependent on the city grid (Loonen et al., 2013; Loonen et al., 2015; Altın & Orhon, 2014; Orhon, 2016b; Böke et al., 2022).

Thanks to media facades, it is possible to create a light show on building facades at night. In today's technology, multifunctional adaptive facade solutions are developed by considering the **media influence** (Altın & Orhon, 2016).

Personal control is required in some cases to terminate or change the automatic behavior of the adaptive facade and personal control is often allowed in adaptive facades (Loonen et al., 2015).

A NEW CLASSIFICATION PROPOSAL FOR HYBRID ADAPTIVE FACADE SYSTEMS

Development of classification diagram

The classification diagram is categorized into smart material properties, smart system properties and purposes. Today, the stage reached in material-based adaptive facade developments is that smart materials have gained a system quality. This situation has brought about the similarity of some of the determined properties, even though the smart material and smart system categories are separate.

In the category of smart material properties, eight characteristics were determined: type of material, type of stimuli, typology of behavior, scales of adaptation, position of material, reaction time (time scales), learning ability and power supply support.

In the category of smart system properties, eight characteristics are included in the classification: working principle, type of stimuli, typology of motion, scales of adaptation, sensor input, reaction time (time scales), learning ability and type of actuation.

In the context of the performance purposes of adaptive facades, seven purposes were determined and included in the classification: thermal comfort, visual comfort, indoor air quality, shading effect, energy generation, media influence and personal control.

The general conclusion obtained from the literature analysis was that the performance purposes of adaptive facades are determined by the properties of the smart material and the smart system. For this reason, it is predicted that the purposes will develop and diversify at the intersection of smart material and smart system properties. Based on this prediction, a classification diagram was developed in which the purposes are located at the intersection. In this diagram, smart material and smart system properties are combined by orienting towards the purposes. It is critical that new material and system properties that will be discovered in the coming years be added to the classification diagram. For this reason, each category is created from cells that develop radially from the center outwards. In this way, it is aimed to obtain a classification diagram that is open to development (Figure 2).

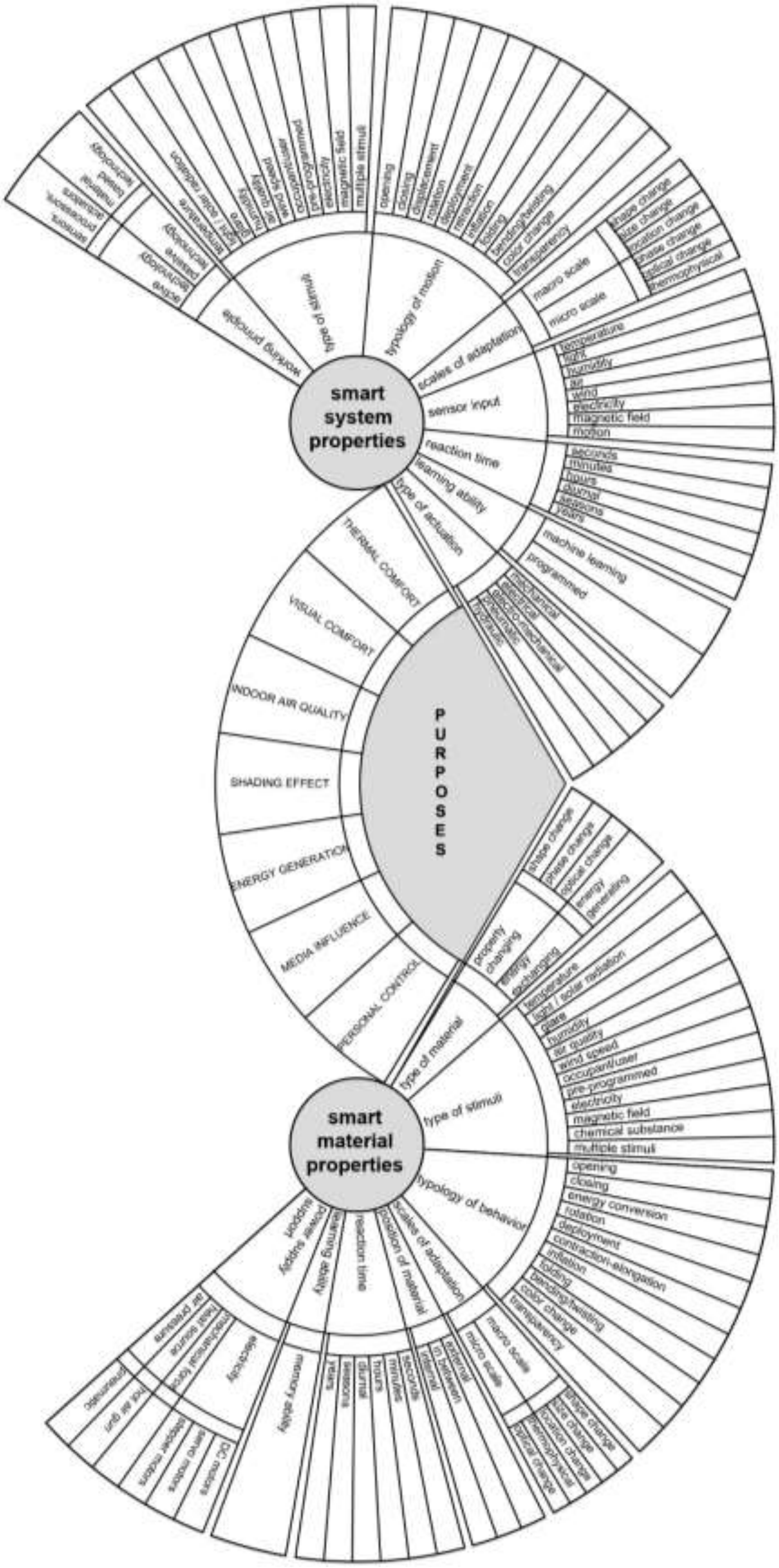


Figure 2. Visualization of the classification diagram for characterization of adaptive facades

RESULTS AND DISCUSSION

Analysis of case studies

An evaluation is carried out through case studies, using the diagram developed to determine the usage potential of the characteristics determined for an adaptive facade with hybrid technology. The case study is limited to examples of adaptive facade systems that either have a smart material or system-based working principle, or utilize both material and system properties. In this evaluation, each case study is first analyzed in the context of the identified characteristics. In the context of smart materials, the evaluation is based on the characteristics of type of material, type of stimulus, typology of behavior, scales of adaptation, position of material, reaction time, learning ability and power supply support. In the context of the system, the evaluation is based on the characteristics of the working principle, type of stimulus, typology of motion, scales of adaptation, sensor input, reaction time, learning ability and type of actuation. In the reviewed adaptive facade systems, the performance objectives are mostly thermal comfort, visual comfort, indoor air quality, shading effect, energy generation, media influence and personal control. Each case study is evaluated according to its achievement of these objectives. All data are summarized in Table 4 according to whether the case studies fulfill the characteristics.

Table 4. Analysis of case studies

Properties / Case Studies	Smart System Properties								Smart Material Properties								Purposes						
	Working Principle	Type of Stimuli	Typology of Motion	Scales of Adaptation	Sensor Input	Reaction Time	Learning Ability	Type of Actuation	Type of Material	Type of Stimuli	Typology of Behavior	Scales of Adaptation	Position of Material	Reaction Time	Learning Ability	Power Supply Support	Thermal Comfort	Visual Comfort	Indoor Air Quality	Shading Effect	Energy Generation	Media Influence	Personal Control
Built Examples																							
  Xicui Entertainment Complex (2008), Beijing, China (Altın&Orhon, 2014; Arup, (n.d); Etherington, 2008)	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓				✓	✓	✓	✓	✓	✓	
 IBA Soft House (2013), Hamburg, Germany (Kennedy&Violich Architecture, 2013; Orhon, 2016b)	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓				✓	✓		✓	✓		✓

Table 4. Analysis of case studies (continued)

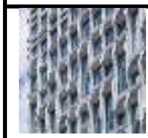
Properties / Case Studies	Smart System Properties								Smart Material Properties								Purposes						
	Working Principle	Type of Stimuli	Typology of Motion	Scales of Adaptation	Sensor Input	Reaction Time	Learning Ability	Type of Actuation	Type of Material	Type of Stimuli	Typology of Behavior	Scales of Adaptation	Position of Material	Reaction Time	Learning Ability	Power Supply Support	Thermal Comfort	Visual Comfort	Indoor Air Quality	Shading Effect	Energy Generation	Media Influence	Personal Control
  Hanwha Headquarters Tower (2019), Seoul, South Korea (UNStudio, (n.d); Frearson, 2014; Altın&Orhon, 2016; Harrouk, 2020)	✓	✓	✓	✓				✓	✓	✓	✓	✓	✓				✓	✓	✓	✓	✓	✓	✓
Full Scale Prototypes																							
  The Integrated Concentrating Solar Facade (ICSF) (2015), New York, ABD (Dyson et al., 2015; Orhon, 2016b)	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓				✓	✓			✓		
 The House of Natural Resources (2015), Zurich, Switzerland (Nagy et al., 2016; Svetozarevic et al., 2016; Svetozarevic et al., 2019)	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓				✓	✓	✓	✓	✓		✓
Reduced Scale Prototypes																							
  Pixelskin 01, 2006 (PixelSkin01, 2008; Loonen, 2010)	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓			✓	✓	✓		✓		✓	✓
  Pixelskin 02, 2006 (Anshuman, (n.d).; *PixelSkin02*, 2009; Loonen, 2010; Tashakori, 2014)	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓		✓	✓	✓	✓		✓		✓	✓

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Table 4. Analysis of case studies (continued)

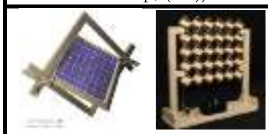
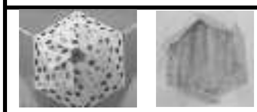
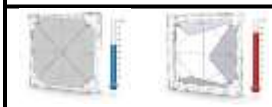
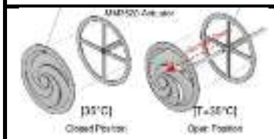
Properties / Case Studies	Smart System Properties								Smart Material Properties								Purposes						
	Working Principle	Type of Stimuli	Typology of Motion	Scales of Adaptation	Sensor Input	Reaction Time	Learning Ability	Type of Actuation	Type of Material	Type of Stimuli	Typology of Behavior	Scales of Adaptation	Position of Material	Reaction Time	Learning Ability	Power Supply Support	Thermal Comfort	Visual Comfort	Indoor Air Quality	Shading Effect	Energy Generation	Media Influence	Personal Control
 Smart Screen, 2009 (Decker ve Zarzycki, 2014)	✓		✓	✓					✓	✓	✓	✓	✓		✓		✓	✓		✓			
 Bloom, 2011 (DOSU Studio Architecture, 2011; Rosenfield, 2012; Xululabs LLC, 2012)	✓		✓	✓					✓	✓	✓	✓	✓		✓		✓	✓	✓	✓			
 Curtain, 2011 (Khoo et al., 2011)	✓		✓	✓					✓	✓	✓	✓	✓		✓	✓	✓	✓		✓			
 Homeo Static Facade System (Decker, 2013)	✓		✓	✓				✓	✓	✓	✓	✓	✓			✓							
 SELF Adaptive Membrane, 2015 (Gonzalez, 2015; Materiability Research Group, (n.d))	✓		✓	✓					✓	✓	✓	✓	✓	✓	✓	✓	✓						
 Adaptive Solar Skin (Raznick et al., (n.d); Orhon, 2016b)	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓				✓	✓	✓	✓	✓		
 TUB Project, 2016 (Li et al., 2016)	✓		✓	✓					✓	✓	✓	✓	✓		✓	✓	✓	✓		✓			

Table 4. Analysis of case studies (continued)

Properties / Case Studies	Smart System Properties								Smart Material Properties								Purposes						
	Working Principle	Type of Stimuli	Typology of Motion	Scales of Adaptation	Sensor Input	Reaction Time	Learning Ability	Type of Actuation	Type of Material	Type of Stimuli	Typology of Behavior	Scales of Adaptation	Position of Material	Reaction Time	Learning Ability	Power Supply Support	Thermal Comfort	Visual Comfort	Indoor Air Quality	Shading Effect	Energy Generation	Media Influence	Personal Control
 Miuso, 2017 (Carl et al., 2017)	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓				✓	✓		✓	✓		✓
 The Air Flower (*Air Flow(Er)*, 2018; Lift Architects, (n.d))	✓		✓	✓					✓	✓	✓	✓	✓		✓	✓			✓				
 SMP Baseline Cell Prototype, 2019 (Yoon, 2019)	✓		✓	✓					✓	✓	✓	✓	✓	✓	✓		✓	✓		✓			
 InVert, 2020 (Sung et al., 2018; TBM Designs, 2020)	✓		✓	✓					✓	✓	✓	✓	✓		✓		✓	✓		✓			
 The Swirl-Type Shading Device, 2020 (Yoon & Bae, 2020)	✓	✓	✓	✓	✓				✓	✓	✓	✓	✓		✓	✓	✓	✓		✓			
 AIF Module, 2021 (Karakoç & Çağdaş, 2021)	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓			✓

Within the scope of the analysis, 20 case studies were examined. Fifteen of these case studies are prototypes that qualify as smart material experiments and power supply support is mostly provided to it with automation systems. For this reason, these cases were included in the analysis as hybrid system case studies. Two of the case studies are full-scale prototypes. These prototypes were analyzed as qualified examples, investigating the impact of the collaboration between smart materials and smart technical systems to achieve facade performance purposes. Three of the case studies are built examples. These built examples represent the goals achieved on the building facade through the cooperation of smart materials and smart systems.

Evaluating of the classification diagram on case studies

The usage density of the characteristics for the reviewed adaptive facades has been visualized through the developed classification diagram. In this context, the color corresponding to the number of case studies has been displayed in the diagram to indicate the usage intensity for each category. While orange and its tones have been used to indicate the usage intensity of the purposes, yellow tones have been used for the smart system category and red tones have been used for the smart material category. This diagram aims to determine the prominent characteristics of adaptive facades (Figure 3).

The 20 case studies have been categorized as active and passive technologies based on their **working principles**. Systems with 13 active technologies and 10 passive technologies have been determined. This result shows that some of the case studies can function both passively and actively.

Within the scope of the case studies discussed in the study, it has been observed that the prominent factor in **the stimulation of adaptive facades** is light/solar radiation and this factor is followed by the temperature factor. Therefore, it can be said that adaptation to the sun is the primary focus in case studies.

The typology of motion has been observed as opening and closing in most of the case studies. These opening and closing motions occur as a result of behaviors such as the rotation and folding of materials in the system. In the case studies, the opening and closing motion is followed by rotation motion and color change. These are followed by folding, bending/twisting and transparency. The case studies have been categorized into macro and micro scales based on **the scales of adaptation**, with 16 macro-scale and 5 micro-scale systems determined. Motion at the macro level mostly occurs by changing the shape and location of the system. In case studies where motion occurs at the micro scale, adaptation is achieved mostly by changing the optical properties of the system.

It has been observed that the usage of light and temperature sensors stands out in the **sensor input** category. This case can be interpreted as a result of adaptation to the sun in case studies. In adaptive facade systems, it is critical that the response to stimuli occurs on time and within its duration. However, within the scope of the case studies, it has been observed that **reaction time** tends to be less emphasized when considered alongside other criteria.

Within the scope of the case studies, it has been observed that electrical-based systems are extensively used for **the actuation of adaptive facade systems**. As shown in Table 4 and Figure 3, other actuation methods, such as heat sources, mechanical force, and pneumatics, have been tested in prototype case studies.

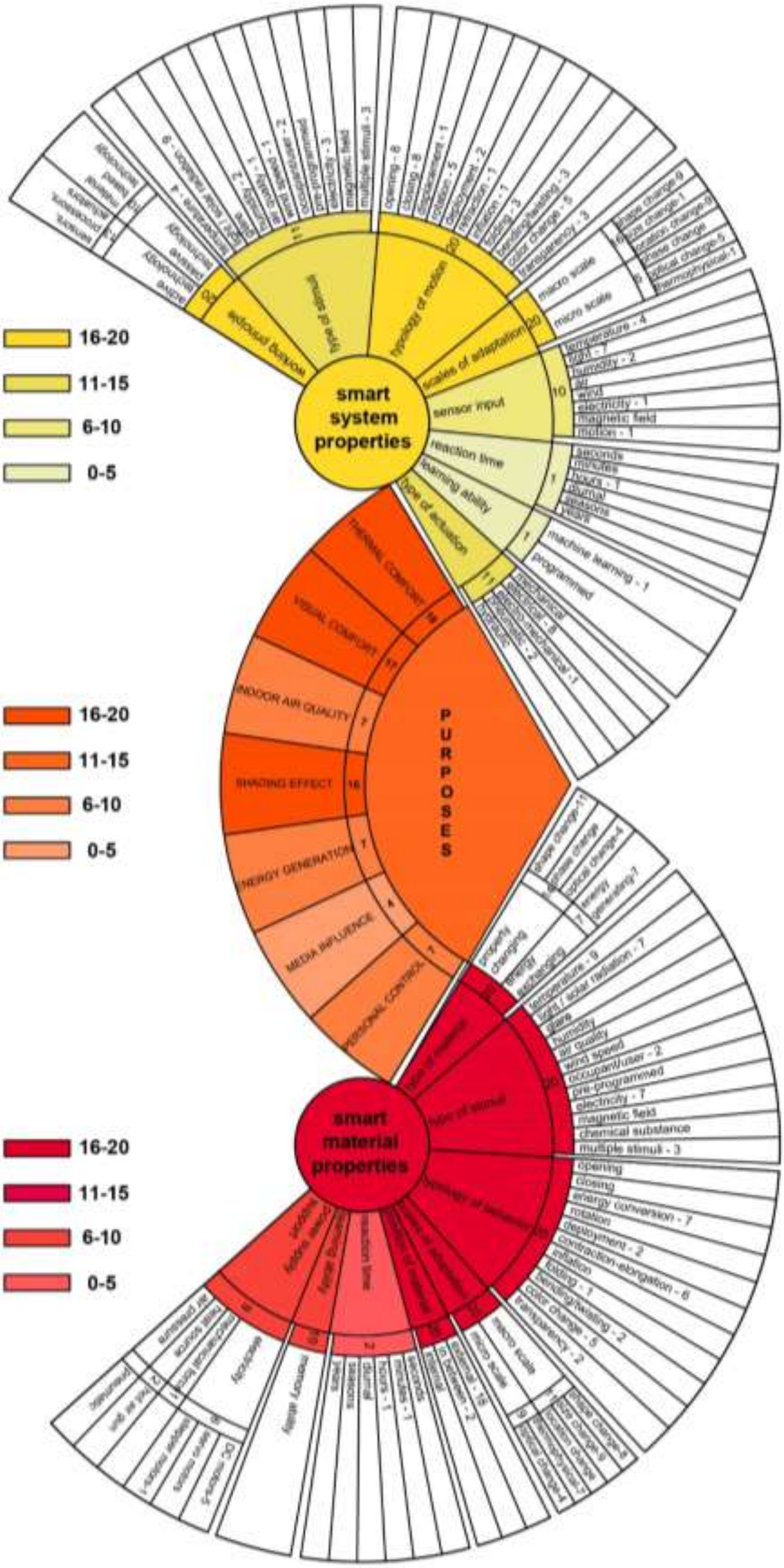


Figure 3. Visualization of analysis of the case studies

When **the type of smart materials** has been analyzed in the case studies, property changing materials have been determined in 14 case studies and energy exchanging materials have been determined in 7 case studies. In property changing materials, adaptation has been mostly observed as shape change (11) and optical property change (4) follows this situation. Within the scope of energy exchanging smart materials, the usage of photovoltaic cells that produce electricity from solar energy has been observed. Most of these smart materials work as sensors in adaptive facade systems, therefore the sensor input category hasn't been included in the classification within the scope of smart material properties.

It has been observed that temperature (9) and light/solar radiation (7) factors stand out as **the types of stimuli** for smart materials in case studies. It has been observed that the electricity as type of stimuli is also used in 7 case studies. In cases where heat or light sources are insufficient to stimulate the smart materials, power supply support is provided through an external electric current.

Energy conversion (7), contraction-elongation (6), and optical property changes (7) (color change and transparency) have stood out as the typologies of behavior in smart materials, respectively. Within the scope of the case studies, energy conversion materials indicate to the usage of photovoltaic cells. Contraction-elongation behavior indicates the intensity of the usage of shape memory alloy wires and springs in case studies. Transparency and color change have been used for shading purposes in some case studies and for media influence in others.

In 11 case studies, the **scales of adaptation** of the smart materials are at a macro level, whereas in 9 case studies, they are at a micro level. While motion at the macro level has been observed in the form of shape (8) and size (9) changes, motion at the micro level has been based on changes in thermophysical (7) and optical (4) properties.

When **the position of smart material** in the case studies was analyzed, the material was mostly located in the external layer. It was used between the internal and external layers in only 2 case studies. In the context of the case studies, it has been observed that material-based adaptive facade studies are mostly experimental and prototypes. Moreover, **the reaction time** of the material is far behind the possibility of the reaction occurring.

Learning ability has been observed in 10 case studies in which shape memory materials demonstrate memory capabilities. **Power supply support** can sometimes be used to stimulate smart materials and sometimes to actuate these materials. It has mostly been observed that electric current support is provided to the system in the case studies.

CONCLUSIONS

In the study, a classification approach was proposed to characterize and increase the legibility of adaptive facades with hybrid technology and an evaluation was carried out through case studies to determine the usage potential of the classification characteristics. The proposed classification approach is constructed into three categories: smart material properties, smart system properties and purposes. Through literature research, specific characteristics of adaptive facade systems for each category were determined. Prominent characteristics for adaptive facades were identified through the case studies.

It can be said that adaptation to the sun in adaptive facades is achieved as the primary objective based on the case studies. Therefore, solar-related functions stand out as key performance aims for adaptive facades. Specifically, thermal and visual comfort, as well as shading effects, are achieved through adaptive facade systems. The prominent use of heat and light sensors in the case studies, as well as the predominance of temperature and solar radiation as stimuli for smart materials, supports this result. Indoor air quality, energy generation, and personal control are purposes achieved on adaptive facades in the case studies, although not extensively. It can be said that these purposes have the potential to be used as success criteria for these facades. Media influence in case studies couldn't stand out for adaptive facades. Adaptive facades are generally designed to respond to environmental factors.

In the literature (Table 1), although adaptive facades are categorized as active and passive, some case studies (especially material-based) can operate both actively and passively. The prominence of electrically-based systems as actuators in the case studies, along with the use of electric current as an external source in material-based systems, supports this result. The general conclusion reached in the study is that the purposes can be achieved more effectively through the cooperation of active and passive systems. Based on the case studies, it can be said that active systems are more widespread, while material-based systems are still in development. Therefore, it is anticipated that research, development, and dissemination of innovative hybrid actuators that benefit from both system and material advantages should be focused on.

One of the general conclusions obtained in the study is that the number of experiments aimed at realizing multiple functions in adaptive facade systems is low, and therefore, multifunctional facades are not widely implemented. Utilizing the collaboration of both active and passive technologies in the development of adaptive systems has the potential to provide effective solutions to this issue. For example, an adaptive facade can fulfill solar performance requirements during the day and transform into a media facade in the evening to provide public services. In doing so, it can be said that the solution space can be expanded with hybrid systems that take advantage of both automation technologies and smart material properties.

The study defines adaptive concepts and presents the properties of adaptive systems in a specific order with the proposed classification diagram. It is predicted that the proposed diagram will assist in the design of innovative adaptive facade systems. In this context, the study has original value as an adaptive facade design guide. Additionally, it is expected that the classification diagram will be developed by adding new properties in the coming years, ensuring its long service life. It is anticipated that it will serve as a basis for classification studies on adaptive facades.

Conflict of Interest Statement | Çıkar Çatışması Beyanı

Araştırmanın yürütülmesi ve/veya makalenin hazırlanması hususunda herhangi bir çıkar çatışması bulunmamaktadır.

There is no conflict of interest for conducting the research and/or for the preparation of the article.

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Ethical Statement | Etik Beyanı

Araştırma etik standartlara uygun olarak yapılmıştır.

All procedures followed were in accordance with the ethical standards.

Copyright Statement for Intellectual and Artistic Works | Fikir ve Sanat Eserleri Hakkında Telif Hakkı Beyanı

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Author Contribution Statement | Yazar Katkı Beyanı

AUTHOR 1: (a) Idea, Study Design, (b) Methodology, (c) Literature Review, (d) Supervision, (e) Material, (f) Data Collection, Processing, (g) Analyses, Interpretation, Resource Supply, (h) Writing Text, (i) Critical Review.

AUTHOR 2: (a) Idea, Study Design, (b) Methodology, (d) Supervision, (e) Material, (f) Data Collection, Processing, (g) Analyses, Interpretation, Resource Supply, (i) Critical Review.

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