RESEARCH ARTICLE

Future trends and main concepts of adaptive facade systems

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Abstract

There is a growing interest in adaptive facade technologies to counter overheating problems and well-being concerns in smart and high-performance buildings. However, traditional literature review studies do not necessarily provide deep insights into the future trends of adaptive facade technologies. To address these limitations, this paper proposes a novel conceptual framework and technological classification for adaptive facades in the future. Our research methodology includes a literature review expert interviews and content analysis. In-depth interviews with 27 international adaptive facade experts were conducted with a focus on the European context. The results categorize the adaptive facade technologies under four promising families and present a conceptual framework that identifies human-centered design, smart building operating systems, service-driven solutions, circularity, and materials as the main drivers of the facade technological advancements. Overall, this methodology yields new and rich qualitative knowledge related to adaptive facades; however, it has certain limitations, such as being time-consuming. The research provides insights on future delivery processes and the future structural trends of adaptive facades. The new categorization and framework articulate the multifunctionality and performance requirements of facade technologies including smartness, automation, comfort, and well-being.

KEYWORDS

classification, content analysis, envelope, framework, in-depth interview, smart

1 | INTRODUCTION

The future of the sustainability of buildings is influenced by three challenging factors. From a social perspective, there is a need to achieve a high level of user well-being and indoor environmental quality (IEQ). At the same time, from an environmental perspective, there is a need to reduce building energy consumption and neutralize building-related environmental impacts.[1,2] Several innovative building envelope technologies and concepts have been proposed as solutions to improving indoor comfort conditions and reducing the environmental impact during the life cycles of buildings.[3]

Particularly, the integration of passive and active design technologies in the building envelope is gaining attention from the research and development community.[4-8]

Thus, the dynamic facades or adaptive facades, as defined by the European COST Action TU1403 (Adaptive Facades Network (2014-2018)), have a profound effect on achieving the three performance requirements in terms of occupant's satisfaction, energy saving, and environmental impact neutralization. Adaptive facades are building envelopes that are able to adapt to changing boundary conditions in the form of short-term weather fluctuations, diurnal cycles, or seasonal patterns.[9-11]

The COST Action TU1403 'adaptive facades network' aimed to group together the knowledge and technologies across European countries and beyond.[10,12] Various definitions for adaptive facades have been proposed including the earliest definition of De Boer.[13] In 2018, Working Group 1 of the COST Action TU1403 proposed another definition.[14,15] Before the above mentioned studies, the books of Knaack et al[10] and Wigginton[16] define adaptive facades more broadly as intelligent skins.[10,16] Both books are written as part of an earlier COST Action C13 on Glass and Interactive Building Envelopes.[17,18] Adaptive facades fall under broader definitions of sustainable facades or high-performance building envelopes.[19] The most recent definition of adaptive facades was proposed by Böke et al.[20] Based on the above-mentioned studies, adaptive facades can be defined as building envelope elements with thermal and/or solar, and/or visual properties (eg, transparency) that vary in time, either passively or owing to an active control. The aim of an adaptive building envelope element is to improve the energy performance and/or comfort in the building under varying outdoor conditions (eg, weather, season), indoor conditions (eg, internal heat gains), and user requirements.

Various studies investigated adaptive facade technologies and products available in the market or under development in experimental laboratories, including dynamic solar shading, electrochromic glazing, and phase change materials. Konstantoglou and Tsangrassoulis reviewed the dynamic operation methods of shading systems and their associated implications in building energy balance.[21] In their paper, Konstantoglou and Tsangrassoulis documented studies on solar shading devices that were published since 1995. Other examples of notable research on solar shading include the work of Tzempelikos, Kim, Valladares et al, and Al Dakheel and TabetAoul.[22-25] Venetian blinds are considered as the most popular shading devices with different control strategies for different climates. Since 2005, an increasing number of studies on chromogenic glazing have been conducted. However, these studies lack use examples and case studies that document the performance of shading control systems and control strategies.

In 2017, Casini provided a review on active dynamic glazing for buildings.[26] The study analyzed electrochromic glazing technology as an alternative to shading systems and investigated their performance in relation to solar and lighting control in relation to the glazing color. The study focused on nanocrystal glass, liquid infill windows, gasochromic windows, elastomer-deformation tunable window, and electrokinetic pixels windows. As a follow-up to this study, Tällberg et al[27] reviewed the performance of smart windows with a focus on simulation studies of thermochromic, photochromic, and electrochromic technologies. This study provided valuable insights by combining technology reviews with building performance simulation for a theoretical reference shoebox

model. The most relevant limitation of this study is related to the assumptions made for the control strategies of smart window glazing.

In 2018, Juaristi, Gómez-Acebo, and Monge-Barrio provided an overview of promising materials and technologies for climate adaptive opaque facades.[28] The paper reviewed previously published studies on the use of phase change materials in building applications and categorizing them under opaque adaptive facade concepts.[29-34] The paper focused on the functionalities and technical requirements of adaptive opaque facade systems and provides insights on phase change material activation mechanisms, reactions, and adaptation ranges. Also, the study by Böke, Knaack, and Hemmerling examined the comprehension of an intelligent system in the context of the facade and in the context of the industry.[20] The study provided a comparative review of responsive facade systems.[5,35] Moreover, the study of HeidariMatin and Eydghai is the most comprehensive study that reviewed adaptive facades for implemented technologies in relation to their benefits and shortcomings.[5]

However, none of the above-mentioned studies investigated adaptive facades to address the large variety of different technological landscapes and assess their potential. These studies use either literature review methods or simulation-based approaches to compare the different technologies but still focus on their past or current performance potential. Literature reviews are a distinctive form of research that intends to generate new knowledge about mature or new emerging topics.[36] The effort to review and analyze the existing literature tends to be limited by the complete reliance on previously published research. The availability and quality of the existing literature influence the outcomes of any literature review and limit its findings to the past or current body of knowledge. Therefore, literature reviews may be adequate qualitative method to create conceptual frameworks for existing literatures. However, a literature review study cannot allow researchers to create frameworks that depict future trends in a field or industry.

In the same time, there is a knowledge gap in the literature on future trends and main concepts of adaptive facades. In general, more extensive research on future adaptive facade technologies in smart and high-performance buildings is required.[5,35] Knowledge gaps exist in terms of the market share of adaptive facades, including the main concepts, the most promising technologies, their categorization, their best fit-to-purpose use, and the distinction between the short-term cyclical and long-term structural trends of adaptive facade technologies. Most studies on adaptive facades are either focused on a single adaptive facade technology (eg, solar shading or AVFs) or focus on structural aspects of adaptive facades, like the work of Bedon et al[37,38] or focus on reviewing technologies existing currently or in the past.[9] No study on the future trends of adaptive facades has aimed to identify

their main concepts and to help understand the structural technological trends in the field of smart and high-performance buildings. Despite the work of Matin et al[5] and Attia et al,[9] both studies did not discuss the main concepts and future structural trends of adaptive facades. There is a need to discover, evaluate, and suggest possible or probable future technologies, thereby helping researchers to evaluate various alternative futures such that they can use this information in their decision-making. In-depth interviews with facade industry experts are well-suited to capture subtleties and unanticipated insights because they provide the interviewees with the opportunities to describe their ideas, structures of thinking, and share their prognosis for the future in relation to the market evolution. Once in-depth interviews are conducted, a consistent overview on the most promising technologies and approaches and evidence-based recommendations can be provided to the facade construction industry.

To address the previous points—to characterize future technologies and explain main concepts of adaptive facades—we exploited the main concepts of adaptive facade technologies by conducting in-depth interviews. In-depth interviews generally are subjective, but this subjectivity can be overcome sufficiently with different validation methods to avoid bias.[39,40] Overall, in-depth interviews are tools that have previously successfully fulfilled research objectives in building engineering.[41-43] Thus far, in-depth interviews have not been performed for assessing adaptive facade technology potential. In particular, in-depth interviews are a unique method with wealth and depth of data that has not yet been analyzed for adaptive facade issues.

Twenty-seven facade-expert interviews are used as sources of data to draw future-related results. Aiming to pursue new knowledge of future trends and main concepts of adaptive facades in buildings, the current paper was motivated by the convergence of insightful data to gain deeper understanding.[44] This study focuses on identifying distinguished ideas of the facade-industry experts, without attempting to generalize for a large population.[41] This qualitative research did not aim to identify replicable or statistically valid results. Rather the study aims to seek singular, particular, and unique aspects.[45] Therefore, the objectives of this paper are as follows: (a) to determine the main concepts of adaptive facades and identify the future trends of technology market uptake, (b) to characterize the most promising technologies of adaptive facade technologies, and (c) to generate knowledge of the future through a novel conceptual framework of adaptive facades in relation to qualitative methods in analyzing facade-related reviews. The research questions corresponding to the objectives are as follows:

1. What are the main concepts of adaptive facades?
2. What are the future trends of adaptive facades?
3. How to characterize and classify the future technologies?

Thus, a novel conceptual framework for future adaptive facade technologies and trends is proposed. The findings succeeded to identify the most promising technologies according to 27 international experts working in four domains of adaptive facade technologies. Implementing the findings may yield environmental and economic benefits. The findings of this research can inform facade designers, operators, owners, and manufacturers and identify the most promising technologies according to experts. Implementing the findings may yield environmental and economic benefits. This study applies content analysis techniques to verbatim transcriptions of 27 interviews to answer the above questions.[44] The remainder of this paper is structured as follows. Section 2 introduces adaptive facades and provides a literature review of related studies. Then, the methods used to extract information from the interviews are provided in Section 3. Next, the results of the research questions are presented in Section 4. Section 5 discusses the findings, strength, and limitations of the in-depth interviewing approach, and Section 6 concludes the paper.

2 | METHODOLOGY

The research methodology used in this paper is qualitative and relies on in-depth interviews and content analysis. In-depth interviewing research method involves conducting intensive individual interviews with a small number of respondents to explore their perspectives on a particular topic. The primary purpose of such in-depth interviews is to provide comprehensive information to understand the underlying experience and expectations of respondents on future trends and main concepts of adaptive facades.[46] As Figure 1 shows, this study is composed of four major parts presented in the chronological order: preparation, conducting interviews, data processing, and validation. The following sections explain the research methodology in detail.

2.1 | Preparation

Prior to the pilot study, a literature review was performed in order to create an initial overview on the state-of-the-art and the state-of-technology regarding adaptive facades and identify the major trends of adaptive facade research. The literature review was based on a previous study by the author and was extended to focus on other specific aspects of an adaptive facade such as its definition, its relation to well-being, comfort requirements, connectivity, control, occupant interactions, and the idea of materials circularity, and adaptive facade project delivery.[9]

A pilot study was carried out to identify relevant themes and concepts related to adaptive facades. This pilot study was
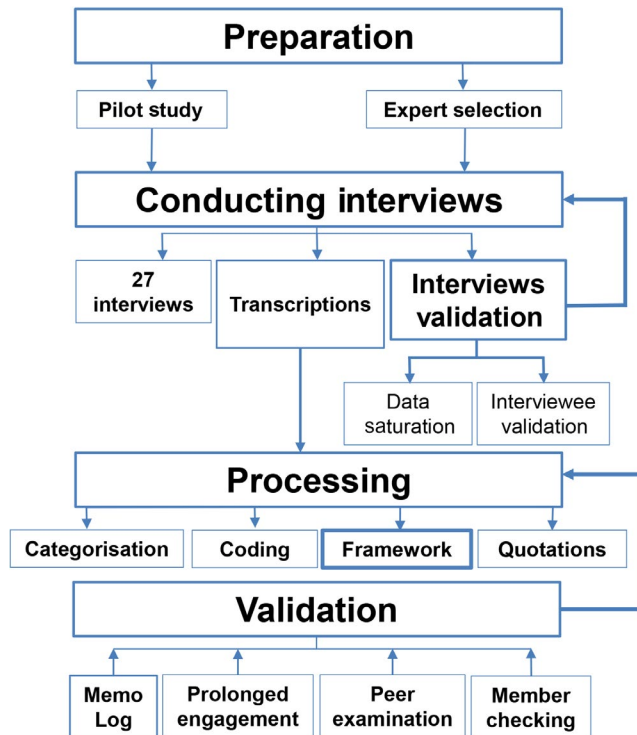
FIGURE 1 Conceptual study framework explains the methods used in this research

FIGURE 2 Distribution of the different interviewed stakeholders

created to define the main questionnaire lines and finally to draw the final questionnaire. The authors set up a pilot study to test and improve the questionnaire's consistency. Peer reviewers were asked to comment and revise the questionnaire to provide critical feedback in order to optimize the clarity and relevance of the questions.

During the pilot study, we realized that the questionnaire is limited by the interviewer's knowledge; with almost every expert interview, new insights on future trends of adaptive facades and significant marketing realities were gained. Therefore, we opted for semi-structured questionnaires. Semi-structured interview questions can be created ahead of time to allow the interviewer to be prepared but they also allow the interviewer to ask questions that are not prepared in advance. The final version of the questionnaire and all previous versions can be found in the report by Attia et al.[44]

2.2 | Conducting interviews

2.2.1 | Interview recording

After conducting the interviews, verbatim transcriptions were prepared. Interviews were conducted with 27 experts. Experts' answers were recorded on a voice recorder, and handwritten notes were taken. Interview records were initially transcribed automatically. Once the interviews were
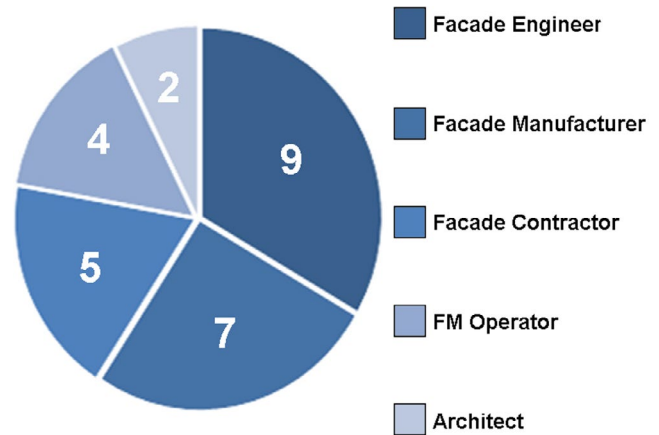
transcribed, the interview transcripts were sent to the interviewees for validation. Interview transcripts were sent to interviewees for content and language checks. Interviewee validation strengthened the transcriptions reliability and ensured that the interview transcripts reflect the interviewee's ideas. However, after some quality checks, we found that automatic transcribing software failed and, therefore, we opted for manual transcriptions. The interview transcription was a time-consuming, but essential, step. It allowed us to precisely go through the expert answers as most of them were not native English speakers.

2.2.2 | Recruitment process

Facade experts were identified during facade-related conferences and were interviewed between 2015 and 2019. Most of the interviewed experts represented architects, facade engineers, facade contractors, facade suppliers, and manufacturers. The distribution of the different interviewed stakeholders can be found in the results (see Section 4). The final number of interviewees and background information can be found in the report of Attia et al.[44] All interviewed experts had experiences ranging from 6 to 10 years and had worked on at least one project with an adaptive facade. The recruitment continued until we reached saturation and heterogeneity.

The continuation of the interviewee recruitments was based on data saturation and interviewee homogeneity (see Figure 1). The recruitment processes ended in summer 2019 when insights and answers started to replicate and overlap. Data saturation was used as a factor to judge the repetition of answers by expert that indicated similar relevant insights. Homogeneity was achieved after interviewing experts from the four major subcategories of adaptive facade industries listed in Section 4. The distribution of different interviewed stakeholders is shown in Figure 2.

2.3 | Data processing

Data processing followed an inductive approach where themes and codes are induced by data, in contrast to the deductive approach that assumes predetermined themes and code. Seven questions, out of the initial 17 questions, were selected for content analysis (see Appendix A and Attia[44]). Most of these questions include advantages of adaptive facades, disadvantages of adaptive facades, and future of adaptive facades interview sections. Our content analysis focused on (a) developing a coding scheme to categorize the main interviews ideas and concepts, (b) developing a framework that summarizes the interview's findings, and (c) a group of significant quotations. Coding is a way of indexing or categorizing the text in order to establish a framework of thematic ideas surrounding it.[47] For framework development, we used the framework method, which is most commonly used for the management and analysis of qualitative data in health research.[48,49] The framework method allows systematically analyzing interview data to produce highly structured outputs and summarized data. Moreover, the framework method has the ability to compare and identify patterns, relevant themes, and contradictory data.[48] The framework method is based on seven chronological steps: transcription, familiarization with the interview, coding, developing a working analytical framework, applying the analytical framework, charting data into the analytical framework, and interpreting the data. The following subsections further explain the data processing method. A detailed description of text processing can be found in the video by Attia.[50,51]

2.3.1 | Coding scheme

We developed our coding scheme to be as consistent as possible with the interview's responses. The coding began by becoming familiar with the data by reading and re-reading interview transcripts and understanding the experts' opinions better. A first version of the coding was developed, and several discussions took place to clarify the code definitions. The coding scheme was revised to ensure that it includes the major concepts and determine codes that articulate these concepts or topics. Unreliable codes were dropped or merged in order to reduce the number of codes the intercoder had to remember. The coding scheme was revised several times to modify the codes and coding instructions; the exercise was repeated until an acceptable level of reliability was achieved.[45]

Next, qualitative data analysis software Atlas.ti (version 8.1/ 2017-12-04) was used to handle the interview transcripts. Large thematic chunks of all the transcripts using the final codes were coded. Then, the co-authors returned individually to these coded transcripts and coded the relevant chunks again for consistency. This coding required a high degree of knowledge; therefore, the coding team was acquainted with it. Moreover, a series of separate "memos" were added to various codes to provide explanations. The memo function enables a second more grounded coding scheme in addition to the first one.

2.3.2 | Develop an analytical framework

The purpose of the coding scheme was not to quantify the data for statistical analysis but to develop an analytical framework that can provide an answer to the following research questions:

- What are the future trends of adaptive facades?
- What are the main concepts of adaptive facades?
- How to characterize and classify the future technologies?

Therefore, after coding, we focused on the organization of the codes under general theme induced categories. A structural scheme was created and visualized. Our classification resulted in new categories, and each category divided into subcategories. In this way, the structural scheme covered all thematic categories and subcategories of the interviewees' answers.

2.3.3 | Quotations

The third approach of data processing involved highlighting a series of separate "quotes" to various pieces of text—an option available in qualitative data analysis software. The quotation function enabled the coder to bracket a portion of text where highly relevant and important statements appeared. Moreover, a series of separate "memos" were added to various quotes to provide explanations. The memo function enables a second more grounded quote selection.

2.4 | Validation

Qualitative research is primarily subjective in approach as it seeks to understand human perceptions and judgments. However, qualitative research remains the most substantial exploratory scientific method that provides valuable insights and interpretations if bias is avoided. Therefore, the validation of the in-depth interviews is important to provide reliable and consistent results. Several validation measures were implemented. The study validation emphasized credibility and strengthened the relevance of the conducted study and results. The following quadrangulation was applied to collect and interpret valid information.

First, *member checking* was used to explore the credibility of results.[53] The interviewees had to revise and approve their interview answers after transcription. Every interview transcript was returned to the participants to check for accuracy and resonance with their experiences.

Second, a *memo log* was created, with handwritten notes during each interview, allowing learning from the data and reflecting on several specific ideas.[39] They were useful for improving the quality of subsequent interviews. More importantly, the memo log was consulted several times during the coding and quotes selection stages.

Third, *peer examination* of the coding took place with another adaptive facade expert who was not involved in this research.[54] The expert was a member of the COST Action TU1403 on adaptive facades. The expert was debriefed on the nature of the research, data collection, and validation approach, and questions were asked to a person who was not in discussion with other experts of the adaptive facades field. This provided a second opinion on the coding process to ensure higher credibility for our research outcomes.

Finally, the *prolonged engagement* of spending more than 4 years (2015-2019) in the field helped to learn or understand the industrial and technical setting of adaptive facades and validate our framework, technology classifications, and main concepts.[55]

3 | RESULTS

This section reports the major findings of this study. Based on the interviewed experts, we present a general classification of the most promising adaptive facade technologies before explaining our coding schemes, thematic categorization, analytical frameworks, and interview quotes.

3.1 | Classification of promising technologies

As a first result of our interview analysis, the experts identified four major families of technologies of adaptive facades that have promising opportunities for high market penetration by 2050. During the early recruitment stages, we did not foresee this classification and we did not seek to find experts representing the different adaptive facade families. Thus, general questions were created for adaptive facades. However, the experts shared their strong agreement to categorize adaptive facades under four main families with high potential market penetration for the coming 20 years. The classification was based on the experts' knowledge on the maturity level, market presence, and market penetration (volume of sales) of each technology. Niche technologies or

technologies under development (even with high readiness level (7-9)) were excluded from the study scope.[56] As shown in Figure 3, the four categories can be categorized under:

- dynamic shadings
- chromogenic facades
- solar active facades
- AVFs

Figure 3 shows examples of buildings that fall under one of the previously listed categories.

During the interview process, several adaptive facade technologies were identified: shutters, roller blinds, venetian blinds, CCF that are naturally ventilated, electrochromic glazing, liquid crystal glazing, thermochromic glazing, building integrated PV, double skin facade, green facade and roof, phase change materials, actively ventilated CCF, and automated operable windows. All these categories are listed in Table 1 according to the new classification. There was a consensus among experts to create two categories for (category 1) dynamic shading and (category 2) chromogenic facades. For category 3, it was discussed whether facades for which the main driving force is temperature difference (eg, phase change materials) should be separated from those for which the main driving force is solar radiation (eg, building integrated PV facades). However, for simplification, all thermal- and solar-driven facade technologies are categorized under category 3 including passively operated double skin facades.[57] The fourth classification *"active ventilative"* is a new category of facades that involves active ventilation. The term "ventilative" is inspired by the work of International Energy Agency Annex 62: Ventilative Cooling.[58] The interviews were helpful in identifying the most promising facade technologies and provided a better overall understanding of these adaptive facade technologies and their characteristics (see Table 1). As a consequence, we changed our recruitment protocol to seek experts that represent the four families to guarantee higher heterogeneity among our interviewees' samples.

3.1.1 | Dynamic shading facades

- Under the dynamic shading category, four adaptive facade technologies composed of moveable parts are present, namely shutters, roller blinds, venetian blinds, and CCF naturally activated, typically associated with a venetian blind integrated in the glazing.
- These moveable parts can be motorized or manually activated by occupants.
- All of these technologies obstruct sunlight. They aim to control daylight, participating in thermal insulation, summer comfort, or cooling savings.

FIGURE 3 Future adaptive facade technologies can be categorized into four families

3.1.2 | Chromogenic facades

- Under the chromogenic facade category, three technologies including chemical aspects, namely electrochromic glazing, liquid crystal glazing, and thermochromic glazing, are present.
- These technologies are not internal or external to the building but directly integrated in the glazing. Their physical properties can change according to the level of voltage and power changing the appearance of the glazing itself, making it more or less transparent.

3.1.3 | Solar active facades

- Under the solar active facades, four technologies are present: building integrated PV, double skin facades, green facades and roofs, and phase change materials.
- The first three are external technologies that are directly in contact with sunlight.
- Double skin facades and green facades and roofs obstruct sunlight; thus, they also achieve sunlight control and summer and winter comfort goals.

3.1.4 | Active ventilative facades

- Under AVFs, two technologies are present: actively ventilated CCFs and automated operable windows.
- These two technologies are based on ventilation. In the case of actively ventilated CCF, the aim is to control the airflow inside the cavity, whereas in automated operable windows, the aim is to control the air entering the building.

3.2 | Coding

Analysis of the in-depth interview transcripts provided 31 codes that reflect all relevant topics, ideas, and insights of experts' answers. Figure 4 lists the selected codes. Comfort and well-being were identified by experts as the most commonly mentioned performance objectives for adaptive facades during the interviews. The code reflects the priority of indoor environmental quality in relation to thermal, visual, acoustic, and respiratory comfort. The second most important group of codes is related to adaptive facades control. The flexible and interactive control and the use of sensors, controllers, and actuators as part of the facade mechatronic systems were highlighted as the secondly most mentioned term or domain during the interview discussions. The variations between manual control and automated control (with the help of artificial intelligence) were discussed intensively. Integrating the control systems and allowing users to adjust their settings at different time intervals in the course of different events (daily or seasonally) were considered as a concern for future adaptive facades operation. The third most common code mentioned by the experts was related to occupants. Occupant's acceptance and interaction with adaptive facades and their education and learning curve when it comes to the use were raised too. The last group that emerged from the codes grouping of Figure 4 is the project delivery and standardization aspect of adaptive facades. The idea of standardization, off-site prefabricated facade elements, and service-driven facade solutions were highly mentioned.

Next, expert answers were coded using the qualitative data analysis and research software Atlas.ti as explained earlier in Section 3.3.1 (see Figure 5). The coding requires immersion

TABLE 1 Adaptive facade technologies, categories, and characteristics

|	Application/purpose	Control	Building type	Technology/materials
Dynamic shadings				
Shutter or equivalent	Obstruction of sunlight, thermal insulation, security, summer comfort, cooling savings, security, heat retention	Manual, motorized or automated (with different levels of automation)	Residential and nonresidential (schools, hospital, offices, public buildings)	Often large wood or PVC, aluminum, integrated blinds in the ceiled glazing
Roller blinds or equivalent	Obstruction of sunlight, thermal insulation, summer comfort, privacy, glare protection, cooling savings			Cellular shades and fabrics (different types and properties)
Venetian blinds or equivalent	See above			Tilting slats and glare control, aluminum and ceiled glazing
CCF: natural ventilated	Sunlight adjustment, daylight control, summer comfort, glare protection, privacy, cooling savings	Electric (motorized) or magnetic	Office buildings	Venetian blinds: aluminum Electrostatic: thin film
Chromogenic glazing				
Electrochromic glazing	Solar gain and daylight control, reduce cooling needs, summer comfort, glare reduction	On demand (active), automated (different levels of automation)	Residential and nonresidential (schools, hospital, offices, public buildings)	Suspended particles, organic and nonorganic coating, colloidal nanocrystal
Liquid crystal glazing	Create privacy spaces, projection screen, and control (solar heat, visible light)			
Thermochromic glazing	Solar gain and daylight control, reduce cooling needs, summer comfort, glare reduction	Environmentally activated (passive)		Thin film or interlayer which changes its crystal structure
Solar active facades				
Double skin facade	Solar gain and daylight control, reduce cooling needs, summer and winter comfort, glare reduction	Active control, environmentally activated, automated	Residential and nonresidential buildings	Two skins with a ventilated cavity (natural or mechanical)
Green facade and roof	See above	Environmentally activated (passive)		Different foliage layers and functional substrates for plant growing
Phase change materials	Solar gain control, reduce cooling needs, winter and summer comfort, heat and solar energy store	Environmentally activated (passive)		Salt or paraffin materials, micro or macro encapsulated into building components
AVF				
CCF: active ventilated	See above	On demand (active), automated (different levels of automation)	Office buildings	

Association of codes with their use number
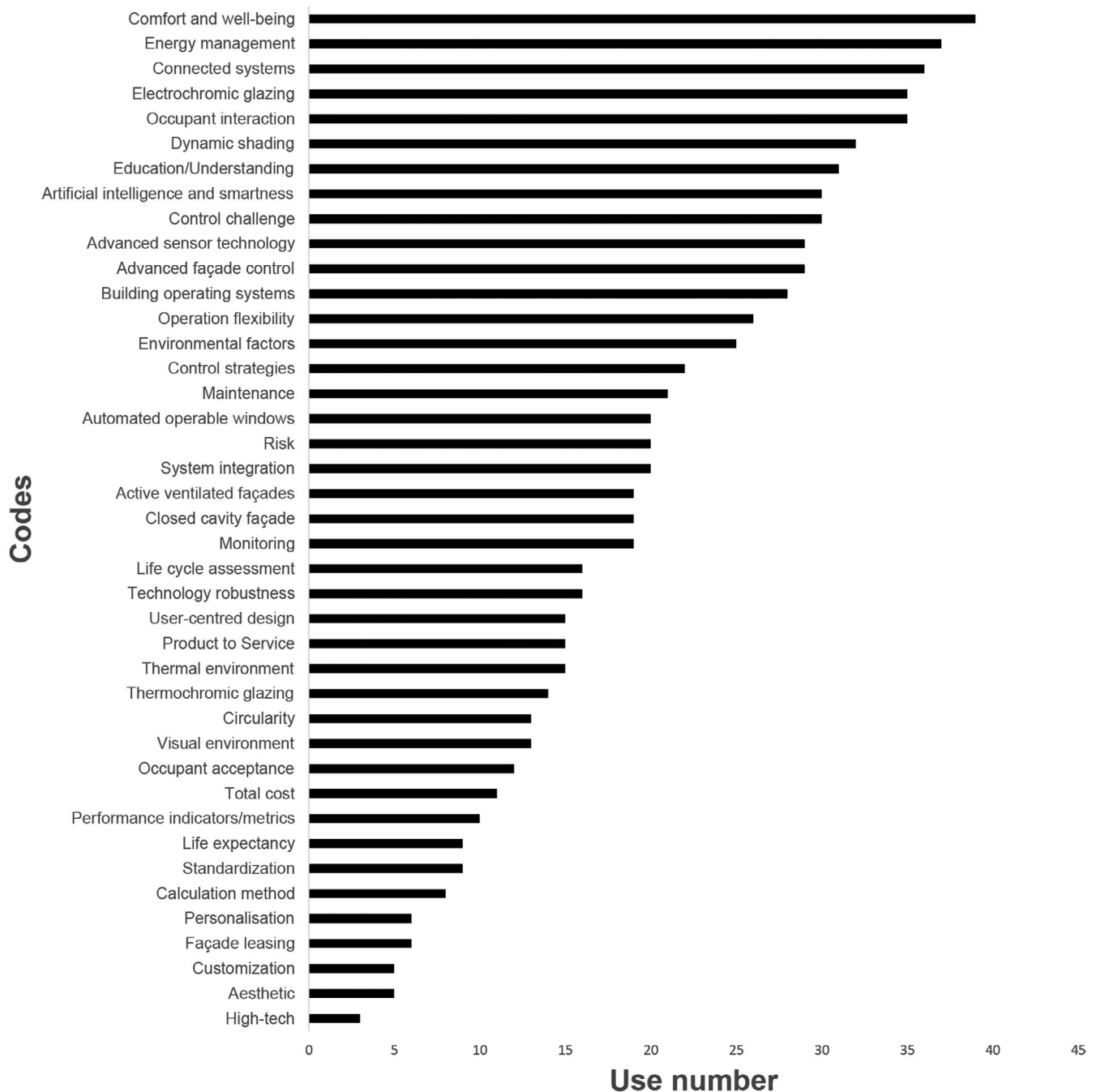
FIGURE 4 Identified codes and their frequencies

in the transcripts whereby searching for common themes across transcripts for each theme that emerged inductively. Figure 5 shows an example of coding the themes/concepts.

All transcripts were loaded into Atlas.ti, and the important coded themes were saved accordingly. Figure 3 quantifies the coding of the transcripts and the most common concepts discussed by respondents in the interviews, such as the adaptability feature of a facade, the influence on performance, user/operator education and understanding, and how respondents interact with the facade system. The figure provides a snapshot of the terms and concept that were frequently mentioned during the interviews.

3.3 | Categories

Identifying the codes allowed highlighting the main concepts and classifying them under major thematic categories. We
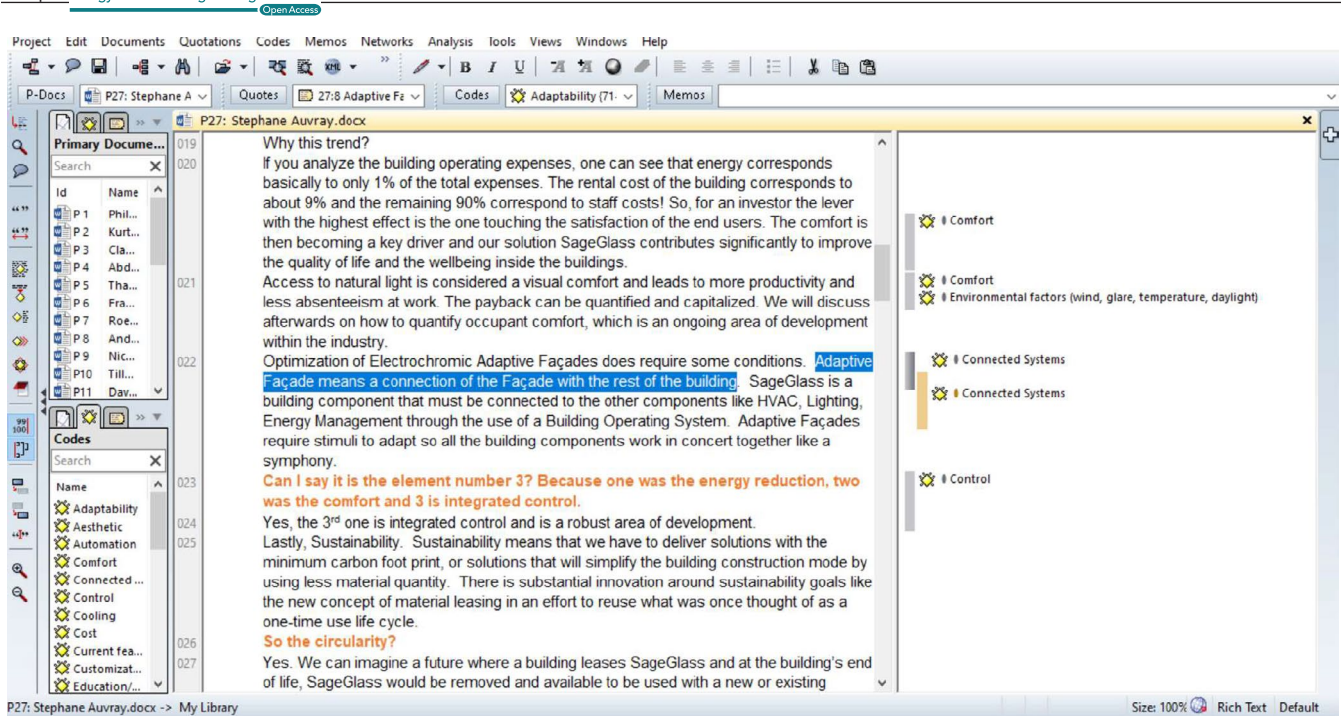
FIGURE 5 Atlas.ti allowed importing word files in order to associate sentences with codes

created four categories that group the main concepts identified in the transcripts. The following section details the categories and subcategories that formed the creation of the analytical framework.

3.4 | Analytical framework

Once the main codes and major categories were identified and validated through peer examination, an analytical framework was created. Figure 6 presents a graph that classifies the major technology trends of adaptive facades under four categories in detail.

Based on Figure 6, we grouped the main concepts and future trends of adaptive facade technologies under four major categories:

- **Human-centered design:** Human-centric design has no formal definition, but it intends to achieve evidence-based facade solutions that balance the different comfort benefits for humans' health and well-being. This includes the interaction and control of the facade solutions to meet users' needs.[59] Our interviewees confirmed that human-centered design is an important added-value driver for the development of the adaptive facade industry. User interaction and comfort personalization in the physical living, learning, or work environments is a cornerstone in the evolution of adaptive facade systems.[60] The digitalization, the new ways of the working, living, and learning, and the higher awareness regarding well-being, productivity, and health concerns stimulate the demand for interactive, comfortable, and personalized environments.[60-63] Human-centered facade design that provides overriding and interaction features for facade system adaptation in real time and based on users' needs is the new promising avenue of adaptive facade systems.[64]

- **Smart building operating (BOS) systems:** Building operating system (BOS) is the cornerstone of adaptive facades. A growing number of facade stakeholders understand that the operation of adaptive facades must be supported by a digitalization and artificial intelligence approaches. BOS is the core software platform for the smart facades because it facilitates and organizes the deployment and use of IoT and digital applications in buildings. The BOS transforms an adaptive facade into a digital service platform that enables connectivity between diverse set of building service systems, control interfaces, sensors, and personal devices. BOS operates over the BMS and other field silos and brings built-in and self-learned intelligence for an occupant-centered deployment.

The smart operation of adaptive facades includes evidence-based management where SMACIT (social, mobile, analytics, cloud, smart grids, and IoT) technologies empower user interaction.[65] This requires a set of control strategies and a complex set of capabilities in terms of storing, integrating, analyzing, responding, predicting, and subsequently learning from users' data to deliver value. The digitalization of working,
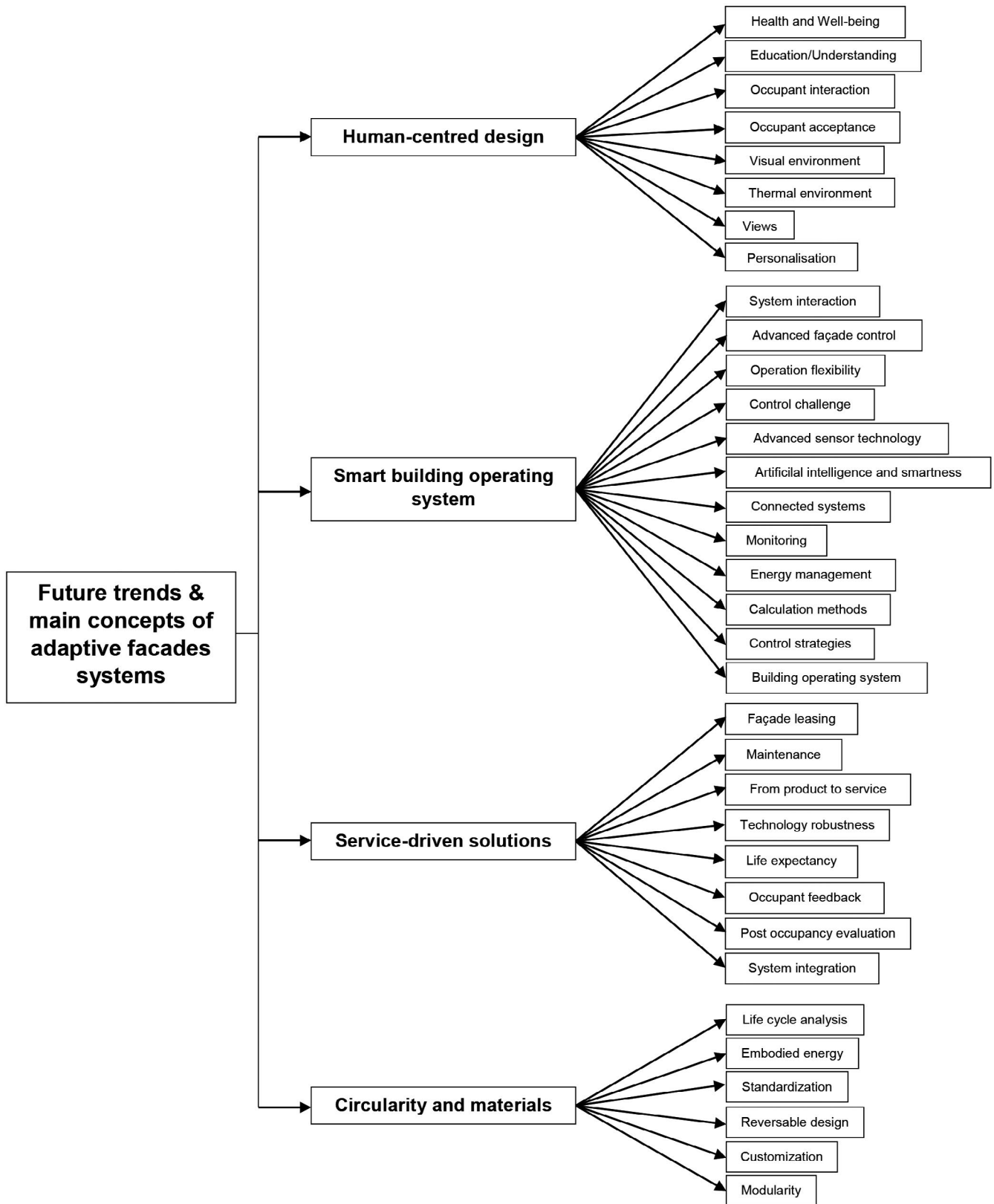
FIGURE 6   Analytical framework showing the global topic structure with categories and subcategories

living, and learning spaces is a structural trend that will provide an additional layer of complexity that requires all facade stakeholders to increase the value of their facade solutions.

• **Service-driven solutions:** Service-driven facade solutions with tangible maintenance and monitoring services are the only approach to address the complexity of digitalization

and human-centered design. Service-driven adaptive facade project delivery shift the performance responsibility from owners to suppliers and manufactures. There is a tendency to align the demand with different supply business models that combines knowledge regarding facade design and engineering (supply-side approach) with the knowledge related to client requirements and performance criteria.[66] Several interview experts mentioned the concept of "facade leasing" as an emerging trend.[67] The service-driven business approach is emerging as a reaction linear, interrupted facade delivery process that fails to integrate the facade technologies with the building HVAC systems, and does not consider the user's response. The risks and uncertainties associated with adaptive facades' operation are pushing forward for a service delivery-based process and transition that will be challenging for the facade industry and construction industry.

- **Circularity and materials:** Resource-efficient facades and low environmental impact facades that enhance the performance of adaptive facade will be associated with limiting the use of materials and other finite resources. The circular economy approach adopted by the European Union (EU) seeks to support preservation of raw materials within closed economic loops. Thus, the facade industry is facing a serious demand to consider the incremental environmental benefit of facade materials during the life cycle of its value chain. This will require different ways of thinking regarding the materials ownership vs disposal and overall low environmental impact of facade solutions.[68] This will accelerate existing trends where clients and designers

adopt innovative technical solutions for lightweight adaptive facades.

3.5 | Quotations

The in-depth interview analysis allowed highlighting several key sentences or sentence segments, called quotations. Based on the extensive interview report, a list of relevant quotations was created as shown in Table 2.[44] We selected the most relevant and representative quotations in-line with the created analytical framework presented in Figure 6. These verbatim quotations were identified as playing a key role in helping to clarify links between data, interpretation, and conclusions, and discussed variously within concepts such as standardization, occupant interaction, control strategies, and customization.

4 | DISCUSSION

4.1 | Summary of main findings

For this study, we identified the most (a) promising adaptive facade technologies and developed an (b) analytical framework for future trends and main concepts of adaptive facade systems. The developed categorizations and framework can be used by architects, facade engineers, facade systems manufacturers, and facade operators. The following paragraphs summarize the main findings:

TABLE 2 Some relevant interviews quotations

Quotations	Interview number
"With electrochromic glazing, there is no more need of maintenance for movable parts or motorization of the facade"	26
"We should allow users to set up the facade preferred position for shading or glare control. Personalized and individualized control is very important increase the uptake of adaptive facades"	4
"Adaptive facades are not remotely control gadgets that can be used without education on how to use them"	4
"We need policy and education to promote the benefits of solar shading"	11
"Comfort is the primary reason why we have building, and we should keep it in mind when designing one"	26
"If you have automation of your facades, you can anticipate what is going to happen and have the facade to react before it becomes a problem"	18
"We need for our adaptive facade and solar control smart sensors who can monitor the current quality level, with interaction for proposals of maintenance"	14
"The feasibility of a Take Back program is still being investigated. There are alternate methods to ensure the recycling, recovery, and re-use of construction materials"	27
"There is substantial innovation around sustainability goals like the new concept of material leasing in an effort to reuse what was once thought of as a one-time use life cycle"	27
"The main story is to make standard control for the adaptive functionality. There must be a control platform that will take care of energy saving and user's needs"	9
"Standardization and prefabrication must be a common practice with a complementary integrated design process"	4

FIGURE 7 Future trends of adaptive facades solutions
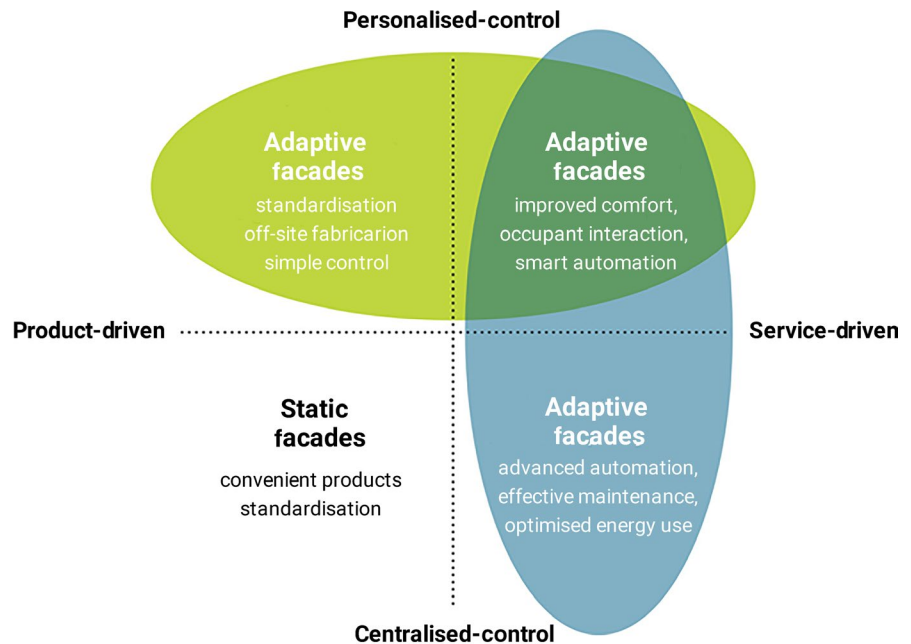
4.1.1 | Promising adaptive facade technologies

As shown earlier in Table 1 and Figure 3, we categorized the adaptive facade technologies under four major families. The classification was based on experts' knowledge on the maturity level, market presence, and market penetration (volume of sales) of each technology. The following families are expected to lead the advancement of adaptive facade:

- **Dynamic Shading:** Dynamic shading is not a new technology; however, it has the widest range of solutions (eg, shutters, louvers, blinds) and the largest market share among adaptive facade technologies. The market value of advanced solar shading is high in association with the growing overheating risk in buildings and move from heating dominated to cooling dominated requirements. Automation and smart readiness are the innovative parts of dynamic solar shading. However, though it is perceived as simple, it is complex to operate.[69] The business growth potential is high (currently 15 billion euros) and can reach 150 billion euros by 2050; if building energy efficiency continues to drive the demand and if further innovations are adopted, for example, dynamic shading can be developed with night ventilation (family 4).[70]
- **Chromogenic Glazing:** Chromogenic glazing is a relatively new technology that will reach a critical mass of market sales in the coming years. Currently, electrochromic glazing is the most robust and promising technology among other chromogenic technologies, reaching an accumulated volume of sales of more than 200.000 m^2 of sales. There are few huge players from the glazing industry with

a focused message on well-being and comfort. However, similar to dynamic shading, automation and smart readiness remain the largest challenges. However, if stringent building energy efficiency codes continue to drive the market demand (inciting low window-to-wall ratio building), the market growth and penetration will be delayed, and the cost will not be a burden for market penetration any longer.

- **Solar Active Facades:** Solar active facades include several new radical technologies that involve a wide range of new possibilities. This family includes double skin facades, green envelopes, and phase change material envelopes. Moreover, this family includes several emerging technologies of adaptive facades that might be promising.[71,72] Currently, solar active facades do not have a large market penetration. Their performance depends on physical and/or chemical and/or biological reaction of materials to the sun and temperature changes with minimal electromechanical intervention. With the exception of double skin facades, solar active facades have limited market penetration. Even double skin facades are not widely used any longer as they can be associated with excessive heat gain in relation to their design.
- **AVFs:** AVFs are an emerging family that will have a high potential in the near future. They include not only active ventilated CCFs, but also active ventilated envelopes with heat recovery units and automatically operated windows (opening). In addition, to achieving thermal and solar control (like families 1-3), they also include active ventilative cooling as a key feature. If the rate and depth of building energy renovations will accelerate and overheating avoidance measures continue to drive the demand, AVFs will have significant competitive growth with families 1 and 2.

4.1.2 | Future trends of adaptive facades

Figure 7 summarizes the future trends of adaptive facades that are concentrated around four structural trends namely:

- Human-centered design
- Smart building operating systems
- Service-driven solutions
- Circularity and materials

As shown in Figures 4 and 7, occupant comfort and well-being emerged as the most important structural trend that influences the market penetration of certain adaptive facades technologies and solutions. Occupant interaction and decentralized control of adaptive facades through personalization and smart automation emerge as the most important structural trend. Monitoring and coupling IEQ conditions to connected facade elements and occupant control with sensors in working and living spaces will become essential. There is a market demand for comfort personalization and service-driven facade delivery for working and living environments.

Also smart BOS will be a structural trend that will benefit from the proliferation of smart sensing and building automation technologies. Advanced automation will allow self-learning control algorithms to make adaptive facades more occupant centered.[73] BOS will facilitate maintenance and efficient operation, which will lead to optimized energy use and carbon reduction in interaction with the energy grid. BOS was identified by experts as a key enabled of future adaptive facades.

4.2 | Strengths and limitations

We are not aware of any published study that aimed to classify the most promising future adaptive facade technologies and set up an analytical framework that identifies future trends and main concepts of adaptive facade systems. Based on the European COST Action TU1403, we developed a consistent overview that characterizes adaptive facade technologies and highlights the major structural tendencies for the future. The methodology used in this study was based on literature review and in-depth semi-structured interviews. The present study's approach remains novel in assessing the market potential of adaptive facade technologies based on experts' experience and views. No other scientific approach would have allowed us to create a rich content with a prolonged engagement exceeding four years of study.

The European and international facade industry must adopt visionary thinking that can open up promising avenues toward human-centered buildings with energy and resource efficient new facade technologies. Therefore, this paper aims

to share knowledge on adaptive facades' state of the art and state of technology in an open and proactive way. This can improve the understanding of practitioners, traders, and industry members to align their designs and solutions with the social, environmental, economic realities, and tendencies of advanced facade technologies.

As mentioned earlier, qualitative research, methods generate subjective results. When we study the ideas of people inside their own community, we do not generalize for a large population. We avoid looking for what is a replicable, reliable, or statistically valid outcome. Rather, we look for what is singular, particular, and unique.[45] Therefore, our verbatim transcriptions from the 27 experts bring new insights based on our subjective approach. To avoid bias, we performed quadrangulation to validate our scientific findings. The interviews have been conducted during a prolonged period of four years with experts from different nationalities and different core specializations. The selection of international experts, the long period of conducting study (*prolonged engagement*), the creation of write-ups and mini-analyses related to what one thinks one is learning during the interviews (*memo logs),* seeking informant or respondent feedback (*member checking*), and discussing our coding with another adaptive facade expert (*peer examination*) are all measures that ensured credibility of our findings. With 27 interviewed experts, we succeeded to characterize the existing technologies and we stopped out interviewing process when the data reached saturation and homogeneity among the four proposed adaptive facade families.

It is acknowledged that the methodology was time-consuming and involved several trial-and-error processes. Once reliability for coding was established, the peer examiner helped us to return to these coded transcripts and coded the relevant text again but with more detailed explanations. This coding required a high degree of knowledge and experienced coders. Thus, without the support from the peer examiner and another expert of qualitative methods in health care, this study would not be possible. This is common when analyzing in-depth semi-structured interviews especially when studying phenomena for which there is little previous research.[48,74] Moreover, our proposed overview and presented framework, in this study, remains only relevant when explored in the content of a previous recent study.[9,19,20,61,75]

4.3 | Implications on practice and research

To convert adaptive facade technologies into mainstream technologies, significant market uptakes must be initiated. This includes innovations in low-impact and climate-responsive renovated buildings through unexplored collaborations between advanced multidisciplinary design teams and innovative facade engineering. Moreover, the market is moving

from a product-based business model to service-driven business model. Embracing the service business model is the most determinant factor for the future development of adaptive facade technologies. It will help Europe grasp leadership early in promising future adaptive facade technologies. Under the new Green Deal, the EU is looking forward to becoming the world's first climate-neutral continent by 2050. Moreover, the European Energy Performance Building Directory (EPBD) highlights the importance of comfort, smart readiness, and high-energy efficiency of buildings will be renewed.[76] The smart readiness indicator developed by the EU mandates the use of dynamic building envelopes with intelligent and connected devices, smart sensors, and controllers, supported by the development of new business models for new energy services.[77] With climate change and increasing overheating risk, there is high potential for the facade industry to renew the basis for its future competitiveness and growth and increase the uptake of adaptive facade technologies in the future. The proposed categorization and framework can allow the facade industry stakeholders to understand the key concepts of adaptive facades and focus on the development relevant future facade technologies. They are based on COST Action TU1403 and are in line with the ISO/AWI 52022-5 that provides calculation procedures for adaptive building envelope elements.

On the scientific level, further defining integrated facade technologies and their control strategies are required. The use of new control technologies emerged as one of the least scientifically explored and researched topics in relation to adaptive facades. A conceptual and theoretical basis for occupant-centered facade control strategies is required. Self-learning control methods are emerging as a potential solution. Self-learning algorithms and an occupant-centered controller approach can be a viable solution to mitigate the discrepancy between occupant comfort and energy efficient control research. Currently, the effects of using advanced control strategies for adaptive facade operation can be overestimated or underestimated. Therefore, future research should investigate the automated controllability and responsiveness of adaptive facades. In the near future, comparative research projects that allow assessing the potential of adaptive facades environmentally, socially, and economically are required.

5 | CONCLUSION

The future and emerging technologies of adaptive facade systems can make a difference with the overheating risks due to climate change and the reduction of energy demand for cooling in existing and new buildings. The main concepts of adaptive facade systems and future trends presented in this paper represent a consensus view of facade experts and technology developers from approximately 20 European countries. The paper provides simple, yet sound categorizations and analytical frameworks for promising and market available adaptive facade system designs and operations (dynamic solar shading, chromogenic facades, solar active facades, and AVFs, see Table 1).This study provides a broad framework, which considers the human-centered design approach of adaptive facades, emerging smart building operation systems (including digital platforms and control strategies), and the transition towards service-driven business solutions within Europe, although it is also likely to be applicable outside Europe.

It will help Europe be the early leader in these future promising technologies and focus on human-centered and smart building operating systems to renew the basis for future competitiveness and growth. This can make a difference in building energy efficiency and occupant productivity and well-being in the decades to come. The study provides valuable insights for facade industry specialists to focus on when facing the challenges of digitization and advanced control and attain a better understanding of human expectations. The study may assist in the implementation of EU standards on adaptive building elements (52022-5/TC 163/SC2 - WG 15 task group) by providing a consistent approach toward categorizing and describing the promising families of adaptive facade system characterizations.

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APPENDIX A

Questionnaire

1. How do you define an adaptive façade? What is the purpose of an adaptive facade?
2. What are the strengths of adaptive facades? (Strength)
3. Do you think that adaptive façade technology is mature to penetrate the market? And Why?
4. What are the risks regarding life expectancy and maintenance of adaptive facades? (Threats)
5. What needs to be done for a better adaptive facades project delivery process and better performance quality?
6. What features would you like to find in the future of adaptive facade?
7. What are the opportunities to increase the use of adaptive facades in buildings in the future? (Opportunities)