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New Taxonomy of Climate Adaptive Building Shell Office Buildings: Focus on User–Façade Interaction Scenarios

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Abstract: As one of the most critical considerations in the contemporary era, sustainability heightens the need to find more suitable solutions for architectural designs. Climate adaptive building shells (CABS) are among the most promising alternatives for achieving sustainability goals by reducing energy consumption. Regardless of technological developments, this type of system has a reputation for increasing the distraction of occupants and consequently decreasing their satisfaction level. This research has been developed to focus on the occupant-centric study rather than technological advancements of the system. This study introduces the user–façade interaction scenarios and applies this classification on CABS office buildings. The purpose of this study is to introduce a new multi-domain taxonomy for CABS office buildings and update the database of this system by adding a new variable focusing on occupants. The study was designed on the foundation found with PRISMA methodology which highlights the lack of occupant-centric research on CABS. The research carried on as a qualitative method with an inductive approach which with the literature review introduced the user–façade interaction scenarios and the latest update of the CABS database. Accordingly, the office cases were categorized within different climatic zones, and later as a correlational study, each case was studied based on user–façade interaction scenarios. Analysis of case databases according to user–façade interaction types clears the lack of development in the majority of scenarios. Lastly, the study concluded by introducing a novel multi-domain taxonomy of CABS office buildings by considering user–façade interaction scenarios. The further value of this study is to be a foundation for future studies on CABS office buildings by considering the occupants as a primary element of the research.

Keywords: CABS; user–façade interaction; occupants' satisfaction; occupant-centric study; multi-domain taxonomy; office buildings

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1. Introduction

In today's world where achieving sustainability is one of the important criteria in architecture, different building shell design concepts have been proposed and studied; one of the most promising proposals is climate adaptive building shells (CABSs). CABSs can be game-changing designs for drastically decreasing buildings' energy consumption while trying to meet occupants' needs [1].

CABS are designed based on dynamism and adaptation. These shells can respond to climatic and environmental changes at different times [2]. The first appearance of this concept in the literature was the study of Knaack et al. in 2007 [3]. Later, different definitions were presented in the literature. However, the complete definition of CABSs was presented by Loonen et al. in 2013 [4]:

"A climate adaptive building shell can repeatedly and reversibly change its functions, features or behavior over time in response to changing performance requirements and variable boundary conditions. By doing this, the building shell effectively seeks to improve overall building performance in terms of primary energy consumption while maintaining acceptable thermal and visual comfort conditions" [4].

In the state-of-art research on CABSs by Loonen et al. [4], they presented the characteristics of CABSs that are essential for understanding the mechanism and principles behind the development of these systems. In general, there are six groups of variables that each CABS can be categorized by:

Physical Domain-Purpose (4 leading groups and 15 combination alternatives): each CABS usually focuses on more than one domain, but in general, the system is more developed regarding thermal and optical disciplines, and minimum focus is applied to the electrical domain;

Scale of Adaptation (microscale or macroscale): in a macroscale adaptation, an individual's movement is the focus of the façade, while in the microscale adaptation, transformation occurs within the material components and is usually not visually perceivable;

Control Types (intrinsic or extrinsic), also called open-loop or closed-loop: in the intrinsic control type, the control does not need external support and can be completed automatically by the system; in contrast, in the extrinsic control type, external support for changing and controlling the system is necessary;

Response Time: this factor can be on the scale of seconds, minutes, hours, days, seasons, or years;

Level of Visibility: CABS adaptations and changes are developed within 5 visibility levels, from the 1st level, at which changes are not visible at all (heat storage), to the 5th level, at which the orientation change can be perceived;

Degree of Adaptation: this factor falls into two scenarios, gradual adaptation or ON–OFF changes [4,5].

1.1. CABS Typologies and Performance Assessment

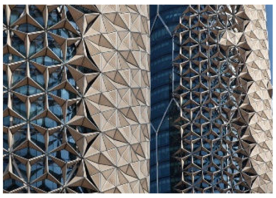
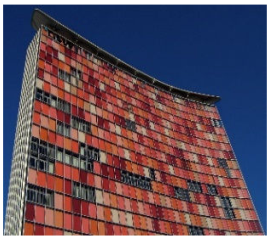
The emerging variables of CABSs introduce different typologies in the research of this field. A long list of terminologies such as passive, kinetic, intelligent, switchable, interactive, and biomimetic, which can replace the keyword "adaptive", creates confusion for researchers [6]. Although all the mentioned terminologies are located under the broader classification of CABSs, this section of the study attempts to present each type briefly through Table 1 and to highlight each typology's relation with users to create a clearer understanding of the topic.

Due to technological developments and advanced control systems, there are samples of CABSs that might fit into more than one typology. Of all the typologies, the responsive façade is the most advanced, in the sense that it considers both indoor and outdoor environmental conditions when interacting with users [7].

Table 1. CABS typologies [8], amended by the authors, 2021.

CABS Typologies	Major Characteristics	Developed from	User–Façade Interaction	Building Example
Active façade	Usage of active technologies Self-adjusting Improve energy savings	-	No	Allianz headquarters 
Passive façade	Passive design solutions No intelligent component	-	No	Telefonica headquarters 

Table 1. *Cont.*

CABS Typologies	Major Characteristics	Developed from	User–Façade Interaction	Building Example
Biomimetic	Imitated from plants and the human body		No	BIQ House in Germany 
Kinetic façade	Working with mechanical systems Acting based on outdoor environment condition	Moveable façade	No	Al-bahar tower 
Intelligent façade	Ability to learn and respond in time Combines automatic and occupant control	Active façade Smart façade	Yes	GSW building 
Movable façade	Adjustable to environmental conditions Mobile systems		No	Oval cologne office 
Responsive façade	Similar performance characteristics to an 'intelligent' façade Usage of sensors, actuators, and control devices	Kinetic façade Intelligent façade Smart façade	Yes	Kiefer Technic showroom 
Smart façade	Operates either by changing internal physical properties or external exchanges		No	Thermochromic polymers-smart windows 
Switchable façade	Transparent components that can regulate energy and light flows	Smart façade	Yes	electrochromic glazing and thermochromics glazing—Rothschild Investment Bank 

CABSs were designed to advance the energy efficiency of buildings and to increase occupants' satisfaction and comfort. The main purpose of CABSs is to reduce the lighting and thermal loads of buildings while creating a comfortable environment for occupants. Screening the literature in this field highlights that enough attention has been given to the performance assessment of CABSs from an energy efficiency point of view, although the number of case studies is still limited [9]. However, the literature review presents an existing gap in occupant-centric research related to occupants' interactions with these systems and their satisfaction assessments.

Occupants have an active role in their built environment, influencing its operation while also being influenced by its design and interior environmental circumstances. Topics such as human–building interactions and occupant behavior have attracted substantial interest in the literature due to recent developments in computer modeling, simulation tools, and analytic methodologies, with the premise of enhancing building design processes and operation tactics.

An accurate "occupant-centric" study puts the user first regarding occupant acceptability, comfort, and satisfaction. To address the topic of how a building might improve the human experience through high functionality or innovation, it is vital first to consider occupants as the ultimate goal of a building design.

Studies as such are critical for improving energy efficiency in buildings in order to address bigger problems such as climate change. It is critical to involve building users in energy efficiency initiatives; otherwise, due to their dissatisfaction, most unique and highly successful technologies become obsolete.

Therefore, this study, with the help of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology, highlights the existing gap in the literature related to user-centered research on CABSs. This systematic review provides opportunities for original studies on CABS office buildings and introduces categorization of these buildings based on user–façade interaction scenarios. The in-depth literature review presents the current developments in the field in regard to occupant-centric studies and user–façade interaction scenarios. Currently, the literature on CABS connected to occupant-centric research is insufficient and fails to convey the complexities of this system and its relationship with the occupants. In the end, this study after analyzing CABS databases with occupant-centric and user–façade interaction considerations, aims to present a few hypotheses that should be considered for further studies in this field.

1.2. Scope and Methodology

From 2014 to 2018, a project on adaptive façade research was developed with the title of COST Action TU1403. This adaptive façade network, through three different working groups, tried to gather the knowledge related to different variables of CABS systems. However, the research on this topic with a focus on user-centered research, remains limited.

A comprehensive literature review shows that there are very limited occupant center studies (pre- or post-occupancy evaluation, user–façade interaction, satisfaction level, user perception, etc.) on this type of system. In addition, a minimal number of case studies have been documented in this field [10] (Figure 1). To support this claim, a systematic study was carried out with the help of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology.

PRISMA may be used to conduct systematic reviews, critical literature assessments, and meta-analyses. The PRISMA strategy employs a number of ways to conduct a systematic search of papers and literature for review-based investigations. PRISMA increases clarity in systematic reviews by addressing all components of the publication, such as the title, abstract, methodology, findings, and discussion. As a result, using this strategy for defining the core problem of this research has been proven to be conclusive when compared to other ways.

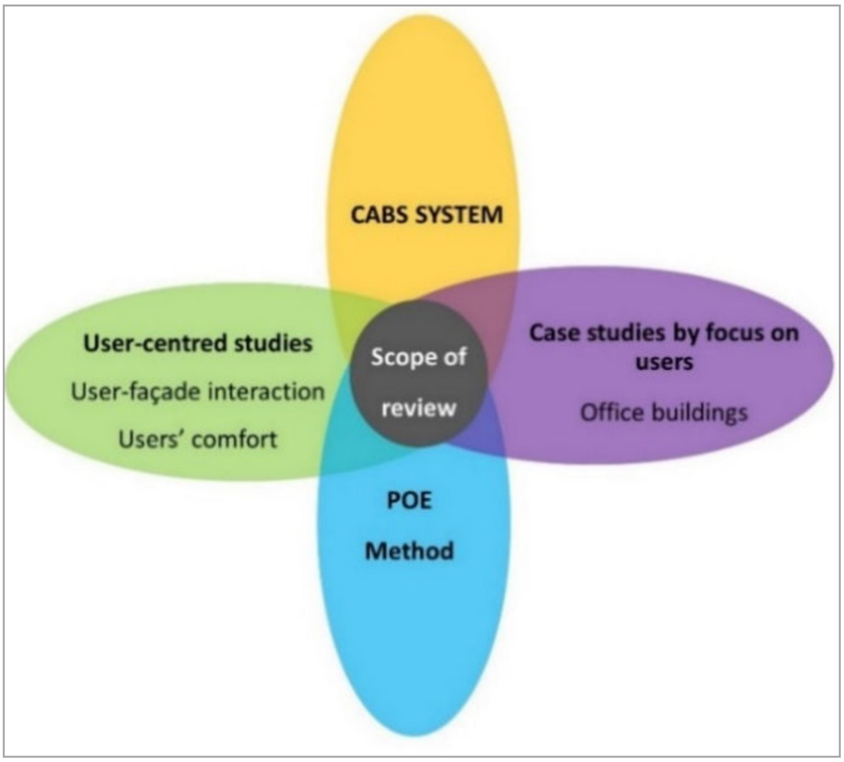


Figure 1. Scope of the study (Authors, 2021).

PRISMA methodology was applied within four main stages of: Identification, Screening, Eligibility, and Included. In the first step, for the identification, publications in the English language from the search engines Google Scholar, ResearchGate, and Web of Science with the keyword CABS were selected. As a result, 112 publications were identified from the databases. After identifying the main sources including the keyword of CABS, 10 publications were removed due to duplications. Accordingly, 102 publications went through the second step: screening. In the screening stage, the abstract and conclusion of all 102 publications were screened. According to this screening process, 86 publications were excluded as they were not falling into the scope of this study. The selected papers had to present data related to user-centered studies, POE, user satisfaction and productivity, or user-centered case studies.

The PRISMA results showed that only 16 publications were eligible for further screening. In this manner, the 16 selected publications were analyzed as the full version to find out the main synthesis of the studies. The last step of PRISMA methodology, highlights that, of these 16 studies, 3 present qualitative syntheses, and none present quantitative results. Application of the PRISMA methodology helped formulate and support the gap identified for this research. Figure 2 presents the results of the PRISMA methodology. The outcome of this systematic review displays the lack of user-centered research in this field.

After application of PRISMA methodology and highlighting the literature gap, this study aimed to review the CABS literature with a focus of occupant-centric studies and user–façade interaction to introduce the latest classification and scenarios. Additionally, on the other hand, review the CABS cases database and focus on CABS office building façade systems. Lastly, with correlational methodology, different classifications of CABS will be presented which, as a result, lead to introducing a new taxonomy of CABS office buildings based on user–façade interaction scenarios (Figure 3).

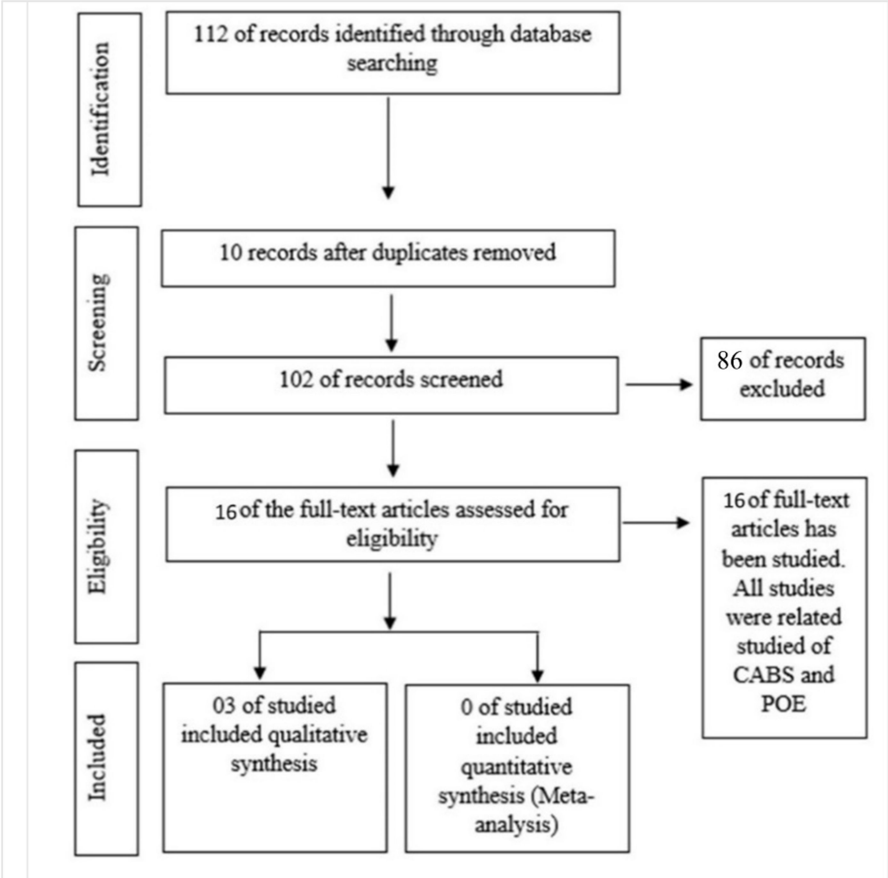


Figure 2. PRISMA methodology results (Authors, 2022).

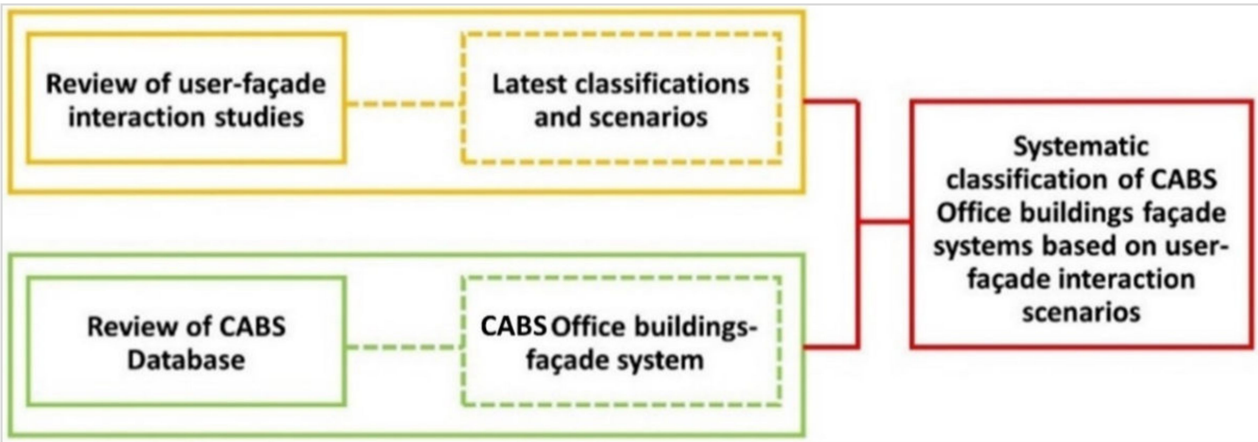


Figure 3. Aim of the research (Authors, 2021).

2. Literature Review

CABS, as one of the most promising developments in architecture, presents a solution that meets energy consumption reduction goals. However, comprehensive studies on this system that deliver actual value from occupants' satisfaction and interaction are lacking in the literature [11]. To date, there is still an open question in the research field of this system: "Are occupants satisfied with having less control regarding the façade of the building?".

Throughout the broad timeline, the literature review shows a direct connection between occupants' satisfaction and their interaction with façades. Some studies documented that even though CABSs increase the indoor environment quality and energy efficiency, in some cases the lack of occupant interaction with the façade decreases the satisfaction level [12]. In regard to CABSs, previous studies cannot cover the complexity and multidisciplinary nature of occupant interactions with the system. Occupant–façade interaction studies mostly focused on one domain. For instance, they focused on the occupant thermal comfort. Thus, it is crucial to understand different alternatives of user–façade interactions in the system [13].

One of the first studies on CABSs with a view toward user-centered studies was presented by Meerbeek et al. in 2014 [14]. They performed qualitative and quantitative research over five months on 40 Dutch office buildings. The study's results show a lack of interest in the automation façade controls from the occupants. However, the study completed by [14] and some other similar studies do not cover the complexity of CABSs and the multidisciplinary and complex relationships between the occupants and the façade. In such complex relations, multiple domains can affect the satisfaction and productivity of users. However, the study of [14] on automation shading control systems gives an overview of the necessity of comprehensive and multidomain research on the CABS and occupants' needs, satisfaction level, interaction and productivity to proposing a CABS that can serve both energy efficiency goals and enhance the satisfaction level of the occupants [14].

In addition to studies such as Meerbeek et al. in 2014, there were two multidisciplinary studies in this field. The first study was performed by D'Oca et al. in 2017 [15], and the other study was performed by von Grabe in 2016 [16]. Although both studies tried to have a multidisciplinary point of view toward the gap in the literature, they still fall short of highlighting the effects of proposed alternatives on occupants. Table 2 gives an overview on current studies in this field, while highlighting a need for more comprehensive studies in this field.

Table 2. Review on CABS user-centered studies from a building science point of view.

Title of Publication	Aim	Main Focus	Conclusion and Synthesis	Complexity of Research
Intelligent façades: occupant control and satisfaction [13]	Investigate the user satisfaction and impact of user control in intelligent façades	Occupant control	Users' satisfaction affected by user's control of intelligent façades of buildings	Not considering complexity of different CABS types
Patterns of occupant interaction with window blinds: A literature review [17]	Reviewing acceptance of users for automatic blinds	Operate blinds	Highlighting the gap in the literature and suggesting further research	Not a multi-discipline study
The contextual factors contributing to occupants' adaptive comfort behaviors in offices—A review and proposed modeling framework [18]	Presenting a framework for studying occupants' behaviors	Occupants' behaviors	Synthesis the of the occupant behavior literature	No synthesis about interaction effects on users' behavior and satisfaction
User satisfaction and interaction with automated dynamic façades: A pilot study [19]	Investigating the user satisfaction in buildings with automated façades	User satisfaction	Synthesizing the further need for adaptive façade algorithm development	Not considering complexity of different CABS types Not considering user interaction with façade
Building automation and perceived control: A field study on motorized exterior blinds in Dutch offices [14]	Underling the user's behavior on usage of different blinds	Occupants' behaviors—venetian blinds	Automatic mood has not been preferred	Not a multi-discipline study
The systematic identification and organization of the context of energy-relevant human interaction with buildings—a pilot study in Germany [16]	Aims to address: which contextual factors are impactful? Additionally, which methods are best suited to predicting the energy-relevant interaction based on the knowledge of these contextual factors?	Multidisciplinary framework	Concluding with identifying the context of energy-relevant user interactions with façades	Does not mention how these alternatives affect occupants

Table 2. *Cont.*

Title of Publication	Aim	Main Focus	Conclusion and Synthesis	Complexity of Research
Review of current methods, opportunities, and challenges for in-situ monitoring to support occupant modelling in office spaces [20]	Reviewing the user's behavior in the context of existing buildings	Occupants' behaviors	Recommendations for further studies	No synthesis about satisfaction level Interaction effect on users
Synthesizing building physics with social psychology: An interdisciplinary framework for context and occupant behavior in office buildings [15]	Investigating the occupants' adaptation behaviors and building control	Interdisciplinary framework	Highlighting the human–building interaction knowledge in the office buildings	Does not mention how these alternatives affect occupants
A literature review on driving factors and contextual events influencing occupants' behaviors in buildings [21]	Highlighting the literature review related to occupants' behaviors	Occupants' behaviors	Presents that beside environmental factors, contextual factors have effects on occupants' behaviors	No synthesis about satisfaction level
Occupancy-based lighting control in open-plan office spaces: A state-of-the-art review [22]	Investigate the occupancy-based lighting control	Lighting control	Further validation is needed for occupancy-based lighting control, and acceptancy level of it by occupants should be studied	Not a multi-discipline study
One size does not fit all: Understanding user preferences for building automation systems [12]	Investigating the preference of users for control of lighting systems in residential buildings	Lighting	In all contexts, no automation over lighting control has been the least preferred	Not a multi-discipline study
Ten questions concerning occupant behavior in buildings: The big picture [23]	Presenting questions addressing the most important aspects related to users' behaviors	Occupants' behaviors	Highlighting an insight related to users' behaviors	Not a multi-discipline study
Comprehensive analysis of the relationship between thermal comfort and building control research—A data-driven literature review [24]	Reviewing two research fields of: optimal building operation (control) and users' thermal comfort, and studying their relation	Thermal comfort	Building controls are focusing on the building energy consumption rather than thermal comfort of users	Not a multi-discipline study
A review of occupant-centric building control strategies to reduce building energy use [25]	Reviewing building control systems and advanced occupant-centric controls	HVAC	Suggest an optimum point balancing the complexity of a system against its potential for saving energy	Not a multi-discipline study
A review of smart building sensing system for better indoor environment control [26]	Reviewing the building sensors and managing the energy saving, users comfort, and IAQ	Sensors	Further studies needed to cover the complexity of the topic and finding satisfaction level in real time	Not a multi-discipline study
Human-in-the-loop HVAC operations: A quantitative review on occupancy, comfort, and energy-efficiency dimensions [27]	Reviewing the hierarchical taxonomy, based on their contributions to occupancy- and comfort-driven human-in-the-loop HVAC operations	HVAC	Hype cycle model was utilized to qualitatively evaluate the developments of different technologies for human-in-the-loop HVAC operations from a research perspective	Not a multi-discipline study

Due to the growing technological developments of CABS, the number of possibilities and alternatives for user–façade interaction has increased. Thus, in many cases, occupants can override the façade and be involved in the control systems. Alternatively, in some cases, façades can analyze occupants' needs and behavior over time and manage adaptation based on occupants and environmental conditions [28]. For these cases, the study of the occupants' satisfaction level is more complex than what was presented in the study of Meerbeek et al. in 2014 [14] or other similar studies.

Understanding the user–façade interaction types has extra importance since it is one of the main variables in user satisfaction evaluation. Studying this factor can help find the actual value of CABSs and the best alternatives for occupants' needs. Related to this matter, a study performed by Alessandra et al. in 2020 [29] introduced a new classification for CABSs based on user–façade interaction. The introduced classification is the backbone of this article [29].

In the study of [29], they present a classification scheme and interaction scenarios for adaptive shells. Based on this research, each scenario was developed with four main components: occupants, building service, logic\control, and façade. In addition to the central element in each scenario, there might be one or more interaction types or sensing types. The four components can have different relationships with each other and with outdoor and/or indoor environmental conditions. In this manner, they can form different interactions. The combination of the four main components, different interactions, and sensing logic can create a variety of user–façade interaction scenarios. Different groupings present 13 different scenarios within five main interaction types. Based on their study, it is possible to investigate each interaction group's advantages and disadvantages, to determine occupants' satisfaction level for each interaction type, to find the environmental factors affecting users' satisfaction, and so on.

The interaction types in Alessandra et al. in 2020 were developed within five main types (Figure 4) [29]:

Dynamic façade–self adjusting (DF-SA): the adjustment will be made by the façade itself. An outdoor condition will trigger the adjustment, in this case there is no need for logic.

Dynamic façade–direct interaction–no control logic (DF-DI-NL): in this classification, the façade can be overridden by occupants. Within three different scenarios, occupants can change the façade configurations according to their need, (a) they can control the façade manually, (b) they can give the commands to the façade, and (c) they get information from the façade which suggests some control options. In this classification there is no control logic involved.

Dynamic façade–logic with environmental sensing–no occupant interaction (DF-L-NOI): in this classification, the control logic is one of the main components of the system. In this case, occupants have no interaction and control over the working mechanism of the façade. This classification can work within two main scenarios, (a) the system's logic sensing the changes in environmental condition and accordingly control the façade or (b) the façade can become smart, the logic starts learning the environmental behavior and start predicting future conditions.

Dynamic façade–logic with automated sensing of occupants (DF-L-ASO): in this system, in contrast to previous classification logic, it is working with occupants and not according to environmental conditions. In this system, logic senses the needs of the occupants and accordingly controls the façade. The same as previous classifications, since the logic is involved, the system can become smart by learning occupants' behavioral patterns, predicting their needs, and acting accordingly.

Dynamic façade–logic with direct occupant interaction (DF-L-DOI): this classification includes the most advanced systems. In this case, both logic and occupants' interactions with the façade are involved. This classification can be divided into five scenarios. In all scenarios, logic conveys the information either from the environment, occupants, or both, and acts accordingly after getting feedback from occupants too [29].

The mentioned classifications and scenarios are used in this article in the interest of analyzing constructed office buildings with CABSs. The following case study section investigates the latest CABS database update and ascertains all the office buildings constructed with the CABS technique. As an original contribution to the research field, selected cases are studied based on user–façade interaction types. The results of the analysis can be beneficial for further user-centered studies in this field.

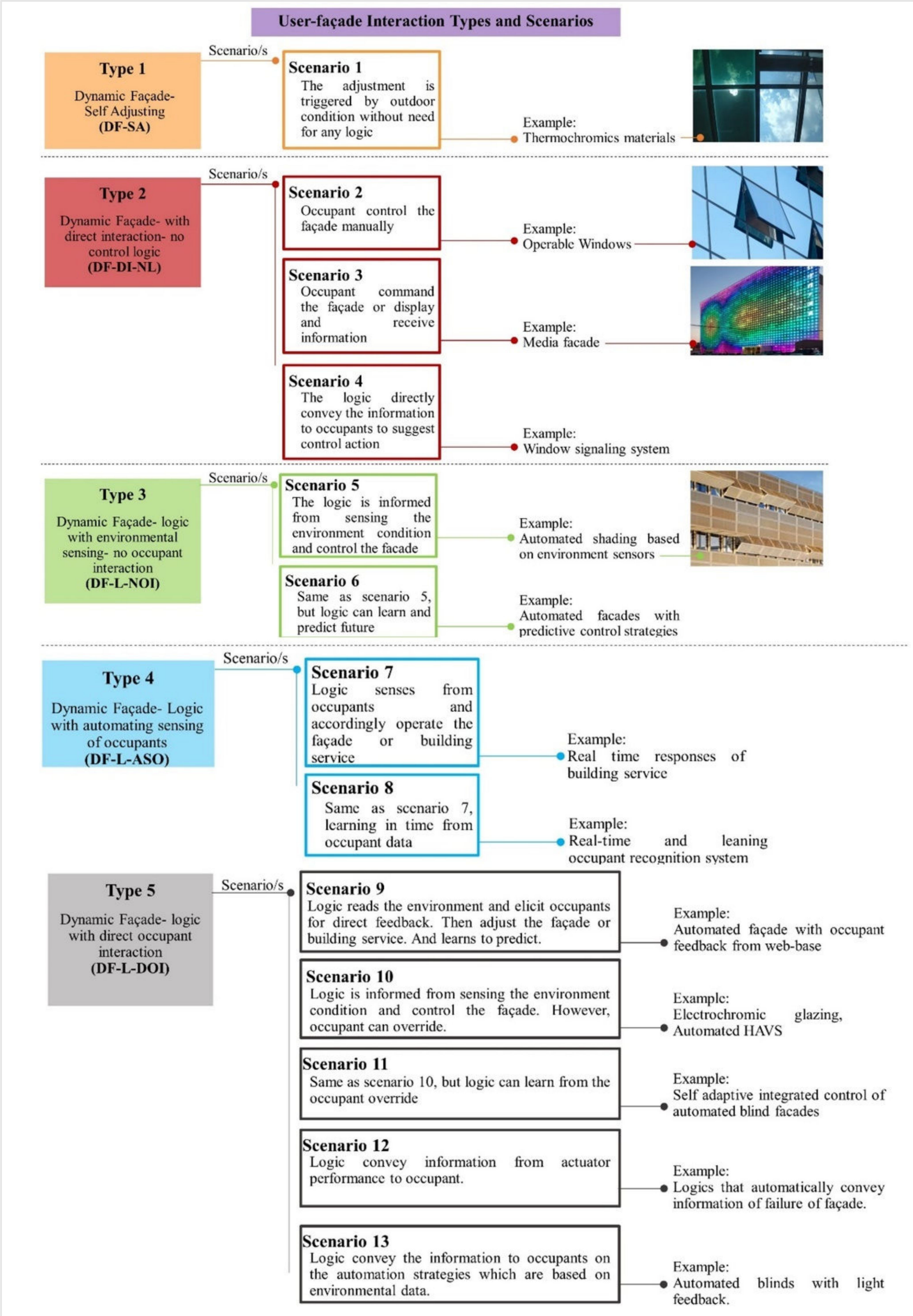


Figure 4. User–façade interaction types and scenarios [29], amended by the authors, 2021.

3. Case Study

In addition to the literature review and before proceeding with the case study, reviewing the CABS database is necessary. The COST Action TU1403-Working Group 1, based on the latest update of their study in 2018, classified CABS cases into three main groups: (1) materials, (2) components, and (3) façade systems:

Materials: These materials can have different levels of refinement and include materials that are inseparably combined, such as bimetals.

Components: This refers to the assembly of different elements. These assemblies can create constructional or functional parts of the façade.

Façade system: This includes transparent or opaque and technical components. It also fulfills all technical actions of the façade such as insulation wind tightness [30].

CABS office building façade systems have been developed within two groups, curtain walls and double skins; thus, as presented in Figure 5, the focus is on these two façade system types.

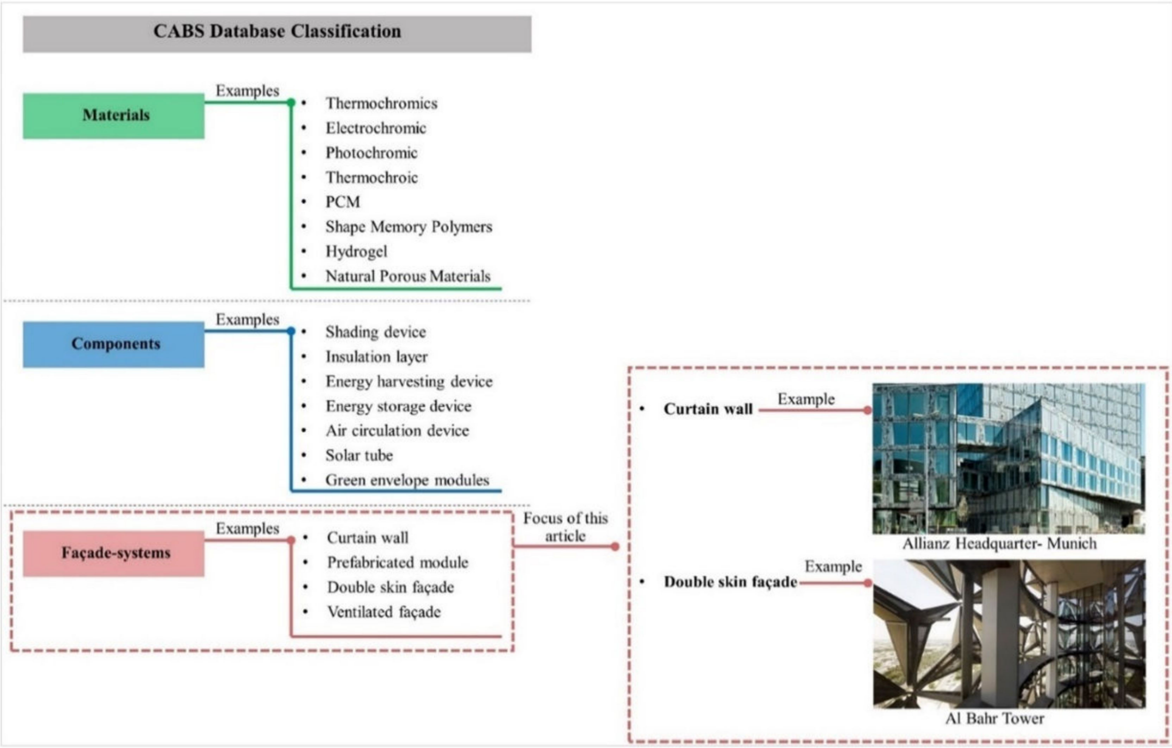


Figure 5. CABS database classification—research focus of this article [30], amended by the authors, 2021.

After the latest update of the CABS database in 2018, 165 cases of adaptive shells from all three groups, façade systems, materials, and components, were documented. Analysis of the database indicates that most of the developed CABS cases are façade systems, at 41% of the total, followed by materials at 32% and components at 27%. The most common CABS types are the double-skin façade (30%) and prefabricated modular system (32%). The functionality purpose of the majority of CABS systems is thermal comfort (30%), followed by visual comfort (24%). Regarding the adaptation timescale, the majority of adaptations are within a second or minute timescale (49% and 38%). The visibility of most cases is presented at the 4th level, which introduces visible changes in the size and shape of the façade (with 42% of cases) [30].

To carry out the case study for this article, two main limitations are applied. Primarily, the main focus is on the façade-system types (as presented in Figure 5). Consequently, material and component types are removed from the research. The second limitation added is the functionality of selected buildings; thus, office buildings are chosen for this article.

The case study section, as a descriptive and comparative study, tries to investigate different aspects of CABS office buildings in the macrolevel context and aims to introduce three classifications of CABS office buildings. First, in Phase I of the case study, selected buildings are categorized based on the climatic zone. This study helps explain the general façade details applied to each building in a specific climate zone. Later, in Phase II, the Phase I result is merged with the user–façade interaction scenarios. Throughout this study, the functionality of façade systems is studied so that they can be assigned to one or more user–façade interaction scenarios. Last, in Phase III, the outcome of Phase II is merged with two other aspects, "CABS typologies" and "control factors". The result of Phase III introduces a multidomain taxonomy of CABS office buildings. Figure 6 presents the structure of the case study.

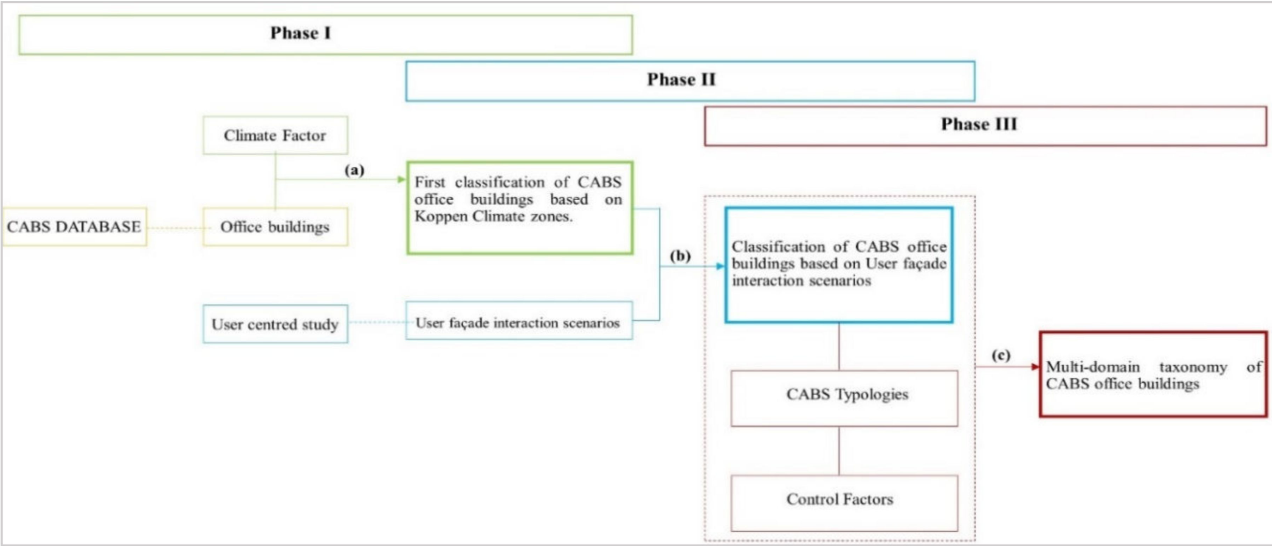


Figure 6. Structure of the case study (Authors, 2022).

Cabs Office Building Façade-System Analysis

Filtering the CABS database based on the mentioned limitations narrows the cases to 24 office buildings with a CABS façade system. As an initial step, a locational analysis is performed. For this study, all 24 cases are entered into the online website "batchgeo.com", and the locations of all cases are presented in Figure 7.

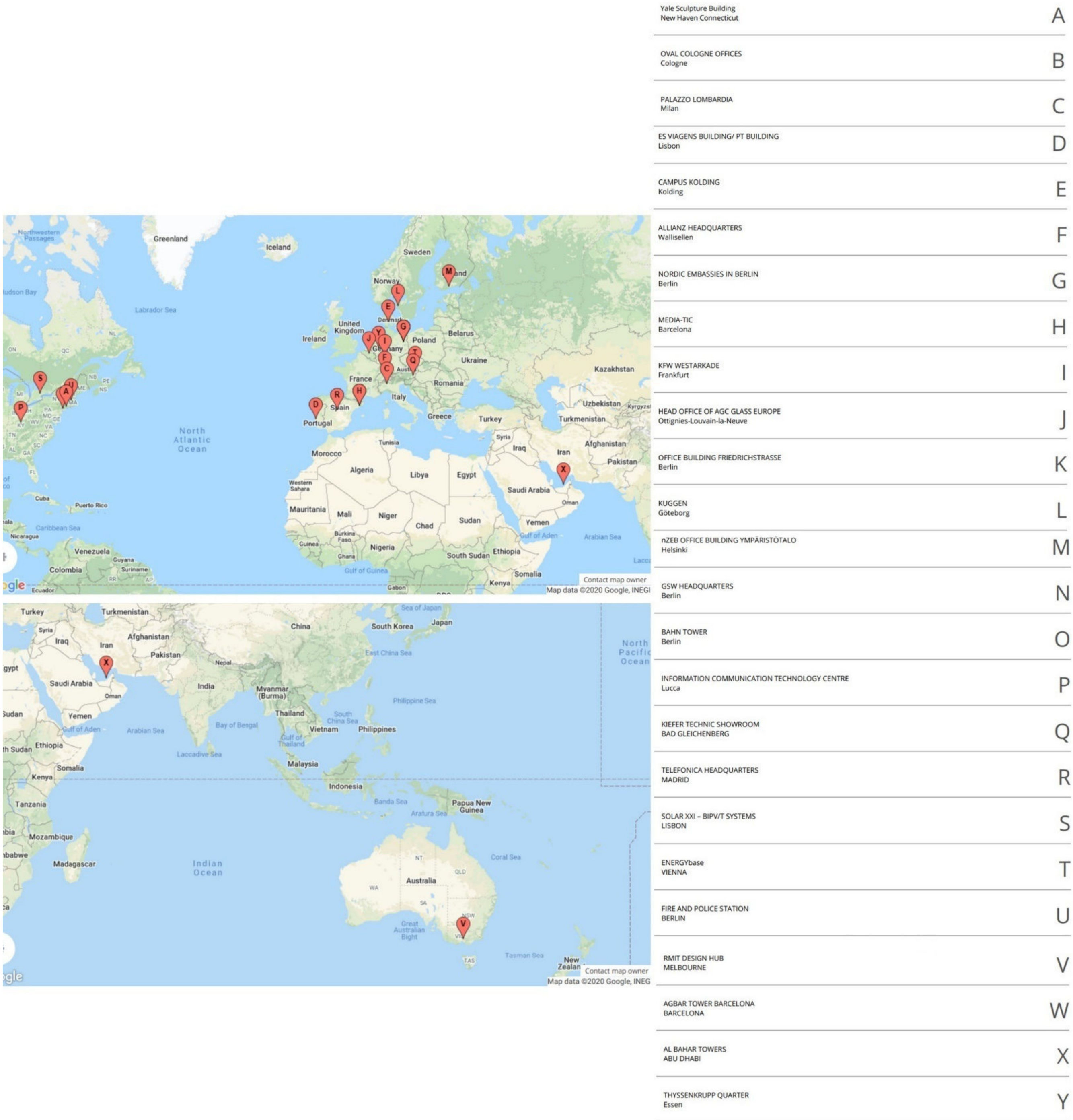


Figure 7. Location map of the CABS office buildings (retrieved from https://batchgeo.com/map/cd08b547f0cb89143f81c38bfac2fc06 (Accessed on 16 December 2021).

Climate differences are significant factors in the design solutions offered by CABSs. In this study, cases are classified by the Köppen climate zone classification [31,32] Through the support of a wide literature review, Table 3 is constructed. This table presents the chosen cases, classified by climate zones and featuring the main façade details of each case.

Table 3. Phase I—façade details of CABS office buildings classified based on Koppen Climate Zones Classification [30,31], amended by the authors, 2021.

Koppen Climate Zone Classification			Building Name	Year	Location	Façade Detail
Level 1	**Level 2**	**Level 3**				
Arid (B)	Desert (W)	Hot (h)	Al-Bahr Tower	2012	UAE—Abu Dhabi	Double-skin façade, shading devices, Ptfe martials
	Steppe (S)	Cold (k)	Media-TIC	2007	Spain—Barcelona	Pneumatic façade and blinds, ETFE
Temperate (C)	Dry Summer (s)	Hot summer (a)	Information Communication Technology Center	2003	Italy—Lucca	Double-skin façade, smart façade, Photovoltaic Panels (PV)
			Es Viagens building	1998	Portugal—Lisbon	Double-skin façade, automatic venetian blinds, exhaust air-gap ventilation
			Solar XXI-BIPV/T system	2006	Portugal—Lisbon	Automatic vertical shutters
		Warm summer (b)	Telefonica headquarter	2008	Spain—Madrid	Double-skin façade, shading devices
	Without dry season (f)	Hot summer (a)	Palazzo Lombardia	2010	Italy—Milan	Building integrated photovoltaic, renewable energy
		Warm summer (b)	Head office of AGC Glass Europe	2014	Belgium—Ottignies Louvain la Neuve	Glass building, movable louvers, automated control, natural lighting
			Campus Kolding	2014	Denmark—Kolding	Shading device, energy saving
			Oval Cologne Office	2010	Germany—Cologne	Automatic vertical shutter, OVAL, color in architecture
			Thyssenkrupp quarter	2010	Germany—Essen	Double-skin façade, smart envelope, steel sheets, energy saving
			KFW westarkade	2010	Germany—Frankfurt	Double-skin façade, low-energy building, ventilation flaps
		Cold summer (c)	Rmit Design Hub	2012	Australia—Melbourne	Sunscreen, bipv, evaporative cooling
			Agbar tower	2004	Spain—Barcelona	Double-skin façade, glass louvers
Cold (D)	Dry winter (w)	Warm summer (b)	ENERGYbase	2008	Austria—Vienna	Passive house standards Double-skin façade, shading devices, stepped façade
	Without dry season (f)	Hot summer (a)	GSW Headquarter	1999	Germany—Berlin	Double-skin façade, solar chimney, natural lighting, louver system
		Warm summer (b)	Kiefer technic showroom	2007	Austria—Bad gleichenberg	Double-skin façade, shading device
			NZEB office building Ymparistotalo	2011	Finland—Helsinki	NZEB, integrated PV, double-skin façade, solar shading
			Nordic Embassies Berlin	1999	Germany—Berlin	Pre-patinated lamellas, sun shading, unified appearance
			Fire and police station	2004	Germany—Berlin	Double-skin façade, shading device, glass shingles
			Office building Friedrichstrasse	2011	Germany—Berlin	Rollers, high-performance façade, operable textile screens, double-skin façade
			Allianz Headquarter	2014	Switzerland—wallisellen	Curtain wall, shading devices, daylighting control
		Very cold winter (d)	Yale Sculpture building	2007	USA—New Haven, Connecticut	Double-skin façade, PV system, smart envelope
			Kuggen	2011	Sweden—Goteborg	Double-skin façade, PV system, smart envelope

The selected cases have been studied by COST Action TU1403-WG1 in detail from technical and economic points of view [11]. However, this study tried to address the user-centered focused study on the cases which has been missing thus far. Table 4 presents a working description of the façade for each CABS office building, and accordingly, they were classified within different user–façade interaction types and scenarios. In addition, a study map was developed with the help of batchgeo.com (Figure 8) that presents the location of each office building with user–façade interaction classification.

Table 4. CABS office building façade-system analysis based on user–façade interaction types and scenarios (Authors, 2022).

#	Building Name	Highlights of the Façade System Design (Bullet Points)	User–Façade Interaction Classifications											
			DF-SA	DF-DI-NL			DF-L-NOI		DF-L-ASO		DF-L-DOI				
			S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13
1	Al-Bahar Towers	* Double-skin façade. * Umbrella-like shading devices that open and close according to the sun path. * Controlled by BMS [33].					x								
2	MEDIA-TIC	* ETFE cladding: solar protection. * Controlling the lighting and temperature. * The first layer is transparent. * The second and third are pattern designs. * This system responds automatically through the triggering of a temperature sensor [34].					x								
3	Information Communication Technology Centre	* Shading devices: the south façade is covered with semitransparent PV panels. * Low-E glazing. * Mobile transparent and opaque sections based on smart development [35].	x												
4	Es Viagens Building/Pt Building	* Double-skin façade. * The air gap ventilation works automatically. * Horizontal shading venetian blinds * The occupants usually override these automatic shading controls [36].										x			
5	Solar XXI—BIPV/T Systems	* Passive technologies. * Designed with PV panels [37].	x												
6	Telefonica Headquarters	* Special glazing. * Double skin. * Glass fins. * The façade results in the interaction of two systems, mutant glass and serialized shadows [38].	x												
7	Palazzo Lombardia	* Double-skin façade. * Photovoltaic panels integration. * Shading protection devices. * Sun shield layout [39].					x								
8	Head Office of AGC Glass Europe	* Glass shading devices. * Removable wooden shading elements [40].		x	x										
9	Campus Kolding	* Applied 1600 triangular shaped steel shading devices. * Automatic system. * Solar cells and mechanical low energy [41].					x								
10	Oval Cologne Offices	* Wide glass façade following the sun path. * Colorful glass folding sunscreens [42].					x								
11	Thyssenkrupp Quarter	* Steel sheet cladding. * Vertical metallic shading devices. * Automatically follows the sun path [43].					x								
12	KFW Westarkade	* Double-skin façade. * Zigzagging transparent panels and ventilation flaps cladding. * Flaps are sensor controlled [44].										x			
13	Rmit Design Hub	* Double skin. * Double glazed inner skin. * Automatic shading devices. * The shading device follows the sun path based on a computer-automated system [45].										x			
14	Agbar Tower Barcelona	* Double skin. * Aluminum and movable glass shadings. * Glass louvers (in 14 angles). * Louvers operate based on sensors [46].					x								
15	ENERGY base	* Stepped façade as a solar generator. * Application of perforated anti-dazzle slats. * The windows are located high so that daylight can penetrate the rooms [47].	x												
16	GSW Headquarters	* Double-skin façade. * Vertical shadings [48].		x											
17	Kiefer Technic Showroom	* 112 panels that are electrically movable in a group or individually. * Three-dimensionality and dynamic façade. * Provides the shading needed [49].		x	x										
18	NZEB Office Building Ympäristötalo	* Double-skin façade. * Photovoltaic cells and solar protection. * Operable windows in atrium [50].	x												
19	Nordic Embassies in Berlin	* Installation of copper lamellas (adjustable in group or individual). The shading devices work through hydraulic control [51].					x								
20	Fire And Police Station	* Glass shingles. * The shingles installed on the windows can be open due to requests. * Shingles operated by BMS, but individuals can override the decisions [52].		x											
21	Office Building Friedrichstrasse 40	* Wide transparent façade. * Controlled with glass and textile and wood shading devices [53].					x								
22	Allianz Headquarters	* Double-skin façade. * Cavity mechanically ventilated. * The aluminum shades for sun control. * Computer controlled [54].					x								
23	Yale Sculpture Building	* Solar shading, triple glazed low-E vision, and operable windows. * Operable windows help natural ventilation. * Interior shadings increase occupants' control [55].	x	x											
24	Kuggen	* Façades extruding out and increasing in size up to the upper floor. * The upper floors create shading for the lower floors. * A rotating shading screen responsive to the sun path [56].					x								

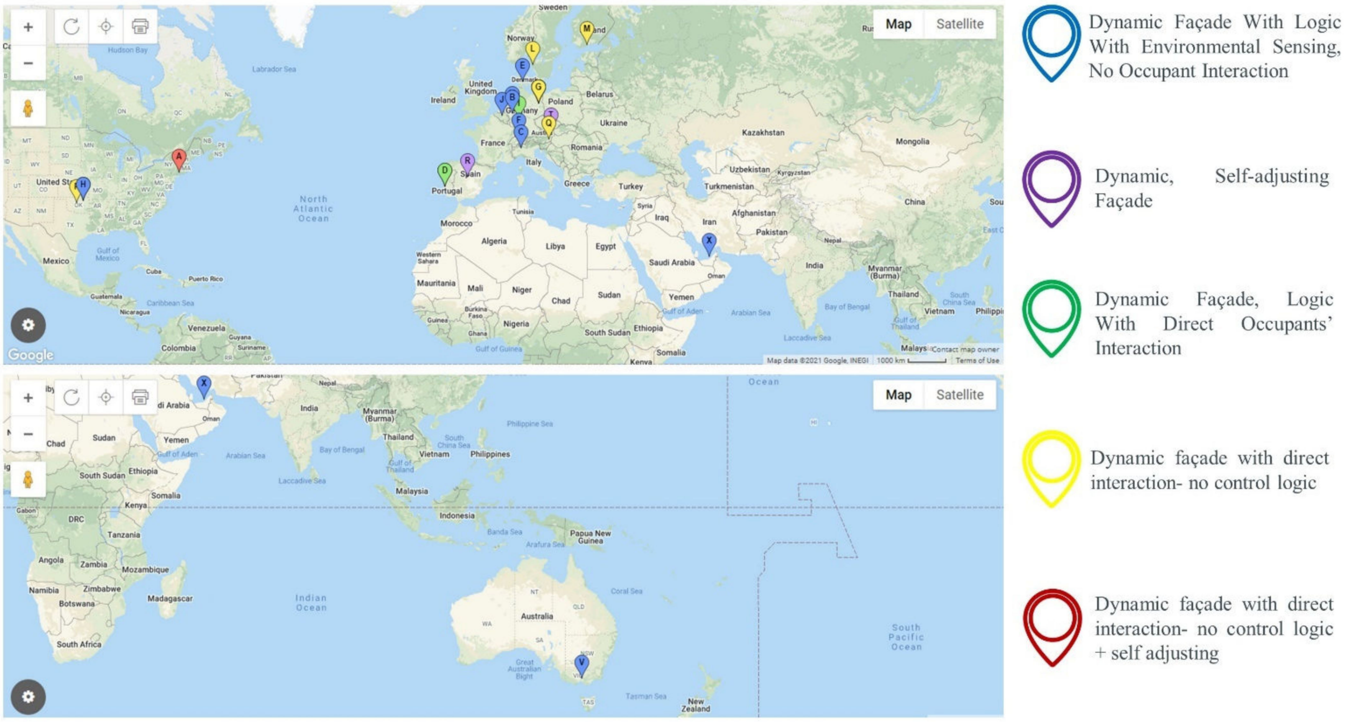


Figure 8. Location of CABS office buildings based on the user–façade categories (retrieved from https://Batchgeo.Com/Map/A7be91e654bf328a43b5eb0f7f2fd389). (Accessed on 16 December 2021).

Analysis of the chosen cases based on the user–façade interaction types shows that cases have been developed within four main interaction types. Figures 9 and 10 illustrate the analytical results from Table 4. Based on this, the cases are almost equally divided into two main types: (1) dynamic façades with environmental sensing logic and no occupant interactions and (2) dynamic façades with direct interactions and no control logic. Interestingly, the two categories mentioned are opposite each other based on occupants' involvement in controlling their workplace. In one scenario, occupants do not have any control over the façade performance, and logic controls everything. In the other interaction type, there is no logic, and occupants or the management of the building is in charge. Thus, for further studies, comparing cases within these two groups to understand occupants' satisfaction and productivity level can provide a perspective for determining a more suitable system from occupants' points of view.

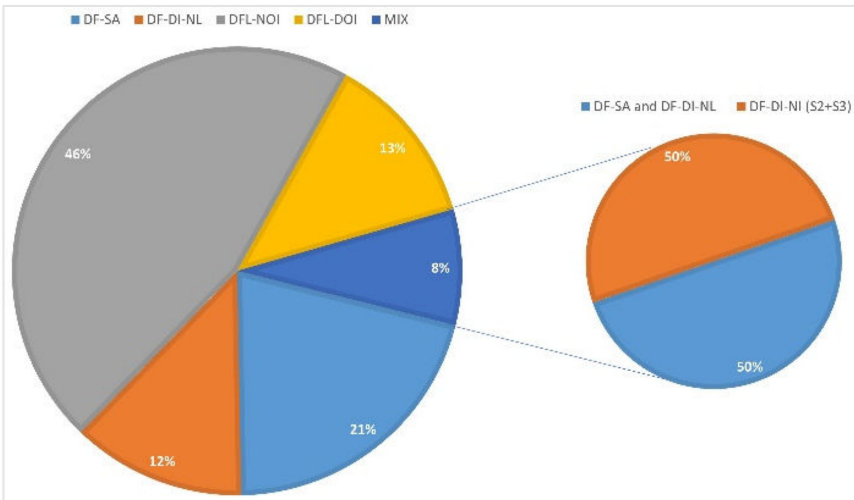


Figure 9. Number of cases within each user–façade interaction type (Authors, 2022).

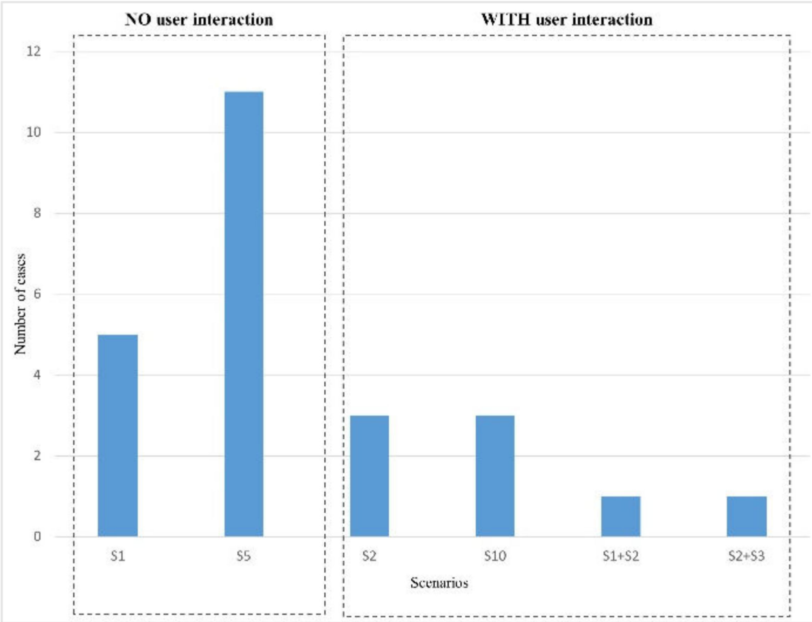


Figure 10. Number of cases per user–façade interaction scenario (Authors, 2022).

Additional analysis of Table 4 can highlight more profiles related to CABS office building façade systems and user–façade interaction scenario development. A study of cases shows that to date, there have been no developments on interaction type 4, dynamic façade logic with automated sensing of occupants (DF-L-ASO), for CABS office building façade systems. The absence of interaction type 4 underlines the missing relation between logic and occupants in CABS office buildings. The second outcome of the analysis shows the lack of development on intelligent logic design. The developed scenarios based on logic work with sensors that act based on environmental conditions, as seen in scenarios 5 and 10. However, this logic has not been developed regarding learning occupants' behavior and needs to predict the future and act accordingly. This analysis draws attention to the need for further development of the logic for CABS office buildings to increase the involvement of occupants in interaction scenarios. Such developments might be useful for higher satisfaction and proactivity levels of occupants.

The outcome of the user–façade interaction studies on CABS office buildings provides an opportunity for taking a step forward and conducting a more complex and multidimensional study. Thus, in Phase III of the case study, CABS office buildings are studied based on CABS typologies (Table 2), control factors (thermal, visual, acoustic), and interaction scenarios. This study presents a multidisciplinary and multidomain analysis that is an original taxonomy for CABS office buildings. The presented classification in Figure 11 can be used for further multidisciplinary studies on CABS office buildings. This taxonomy, by including different macrolevel contexts, can be beneficial for CABS studies since it matches the complexity of the system.

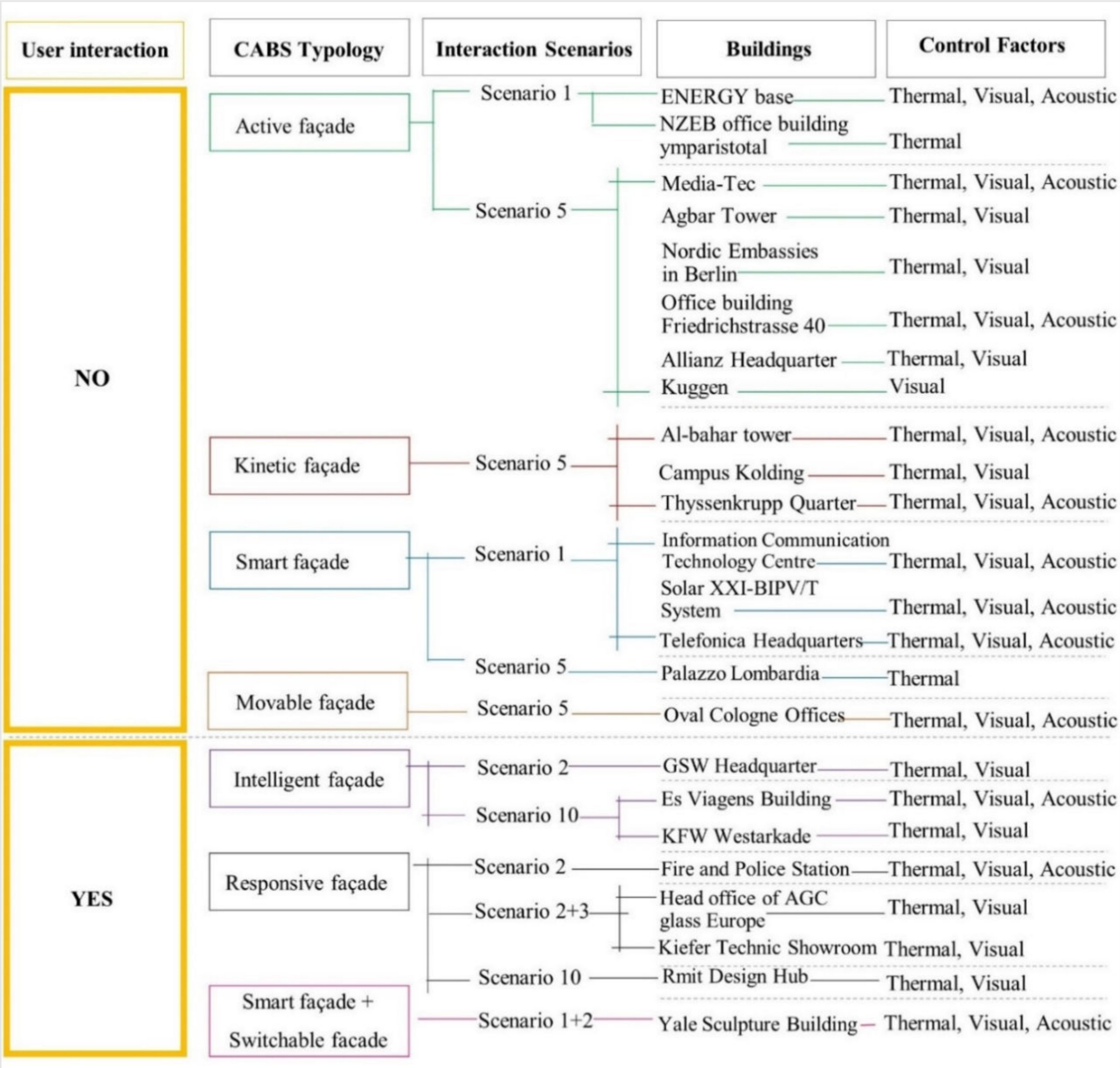


Figure 11. Multidomain taxonomy of CABS office buildings (Authors, 2022).

4. Conclusions and Recommendations

This study presented descriptive research from the literature related to user-centered studies, user–façade interaction types and scenarios and, moreover, overlapped this classification with CABS office building façade system design. The aim is to document a systematic outcome of cases that can help better explain occupants' relations with CABS designs and can be a solid foundation for further studies on this matter. This study presents a multidomain taxonomy of CABS office buildings through three phases. This classification covers the multidisciplinary nature and complexity of CABSs to some extent.

The general outcome of the literature presented that there are still no systematic studies investigates the relation of occupants' comfort and productivity with CABSs. There are no studies investigating the relations of occupants and each specific type and scenario of user–façade interaction discussed in advance. There is a need to focus on each type and conduct a comparative study on the level of satisfaction and productivity in each building.

The results of the correlational study (CABS cases and user–façade interaction) on office buildings highlights the lack of advancement on the majority of user–façade interaction scenarios. Analysis of case databases according to user–façade interaction types shows the advancement of the system on mostly two scenarios: (1) dynamic façades with environmental sensing logic and no occupant interactions and (2) dynamic façades with direct interactions and no control logic. In case 1, the occupants have not been considered as a component in the development of the system. This lack of control over the façade can increase the chance of occupants' dissatisfaction. In the second case, occupants can override the façade by having full interaction; however, in this case there is no logic developed in the system to analyze the environmental condition and suggest the best solutions which can lead to energy overconsumption.

The study on CABS office buildings highlights the need of advancement for all user–façade interaction scenarios especially for the scenarios which include the occupants (either with direct interaction or the logic learning occupants' behaviors) to increase the satisfaction level. Additionally, the façade systems should be developed with a logic system to analyze and suggest the optimum solutions to control the energy consumption of the building.

This study highlights the need for considering occupants as one of the main components while developing the system and creating several hypotheses that can be investigated in future.

Different visibility and adaptation time scales of office buildings can affect productivity.

Users with direct interaction with the shell have a higher level of satisfaction.

The general satisfaction level is not the same in CABS office buildings with different user–façade interaction types.

Improvement in the usage of intelligent logic can address occupants' satisfaction.

Future research should test the discussed office buildings in this study with a user-centered focus. Many variables were presented in this study, such as the typology of the system, control factors, and interactions, and all these variables impact occupants' satisfaction and productivity in workplaces. Due to the system complexity, the study should be undertaken during different times of the year (various environmental factors should be considered). Therefore, broad research with a large sample group should present the occupant experience in these buildings.

As a continuation of this paper, the authors aim to implement a comparison study on CABS office buildings with different interaction scenarios by practicing POE. Future research will present quantitative data and a clear understanding of which system is more suitable for occupants' satisfaction and productivity.

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