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Paper Title:

Occupant-Facade interaction: a review and classification scheme

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The interest in occupant interaction with building controls and automation systems is growing due to the wider availability of embedded sensing devices and automated or intelligent building components that can integrate building control strategies with occupant-centred data and lead to greater occupant satisfaction and reduction in energy consumption. An area of particular interest is the interaction strategies between occupants and the so called automated facades, such as dynamic shading devices and switchable glazing. Occupant-Facade interactions are often disruptive and source of dissatisfaction because of conflicts between competing requirements, e.g. energy-efficiency and indoor environmental quality. To solve these conflicts, expertise from several disciplines is required, including Behavioural Science and Building Physics, but the absence of common research frameworks impedes knowledge transfer between different fields of expertise. This paper reviews existing multi-disciplinary research on occupant interaction with facades, buildings and automation systems and provides a new classification scheme of Occupant-Facade interaction. The scheme is based on an extensive review of interactive scenarios between occupants and facades that are summarised in this paper. The classification scheme was found to be successful in: 1) capturing the multidisciplinary nature of interactive scenarios by clarifying relationships between components; 2) identifying similarities and characteristics among interactive scenarios; 3) understanding research gaps. The classification scheme proposed in this paper has the potential to be a useful tool for the multi-disciplinary research community in this field. The review also showed that more research is needed to characterise the holistic and multi-disciplinary effect of occupant interaction with intelligent building components.

Keywords: occupant interaction, building automation, smart buildings, intelligent facades, personal control, occupant satisfaction

Abbreviation list

AI	Artificial Intelligence
B	Building Service
E_i	Indoor Environment
E_o	Outdoor Environment
F	Facade
HCI	Human Computer Interaction
HVAC	Heating Ventilation Air Conditioning
I	Direct Interaction
IAQ	Indoor Air Quality
IEQ	Indoor Environmental Quality
O	Occupant
L	Control Logic
L_m	AI-Enhanced Control Logic
S	Automatic Sensing

1 Introduction

The requirements for high-performance buildings have become more complex in recent years [1] due to the need for low-carbon construction [2] and the growing awareness relationships between indoor environmental quality (IEQ) and occupant health, wellbeing and productivity [3]. Building automation is a promising solution for low-energy buildings, particularly when actuation systems and ubiquitous sensing devices are used in conjunction with Artificial Intelligence (AI) (Figure 1.a) in and outside buildings [4]. AI algorithms can process many information streams from sensing devices, and allow intelligent building components to make autonomous decisions that aim to optimize operational building performance [5]. For instance, environmental control systems can be automatically adjusted to anticipate or respond to changing environmental conditions and meet occupant comfort requirements whilst minimising energy use [6].

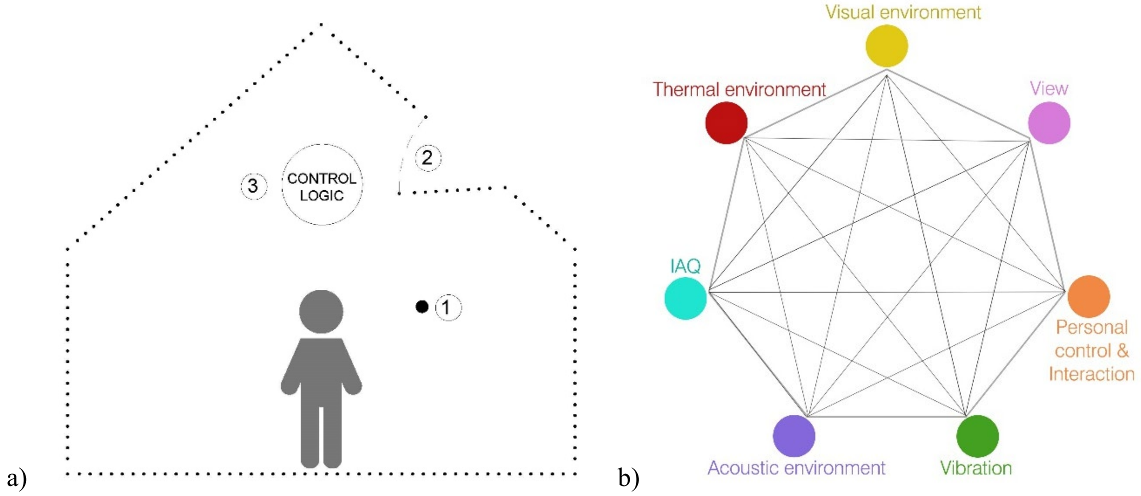


Figure 1 Building automation principal components (a): 1. Sensing devices, 2. Actuation systems of building components, 3.Control logics; (b) Occupant multi-sensorial requirements for holistic environmental satisfaction: Thermal comfort, Visual comfort, View, Indoor Air Quality (IAQ), Personal control and Interaction, Vibration control and Acoustic comfort [7]

This growing number of so called smart / dynamic / adaptive / intelligent building components has also increased the number of possible interactions that occupants can have with building components. For instance, occupants can now communicate with automated building control strategies and actively influence them [1]. Automated or intelligent control systems can also monitor occupant behaviour and response to adapt to and learn from the daily routines of people [8]. However, despite the level of technological development of building automation systems, occupants are often dissatisfied with control strategies and related interactions with automated systems [9]. Automated control systems often give rise to conflicts, namely: 1) Occupant needs for personal control and energy-efficient automation strategies [10]; 2) Energy-efficiency strategies versus IEQ [7], [11]; 3) Different needs for occupant holistic satisfaction, such as maximising daylight whilst controlling overheating [12]; 4) Complexity and Ease-of-use [13]; 5) Individual expectations in multi-occupant spaces [14](Figure 1-b). A well-considered design of smart building components requires therefore to meet multi-domain requirements and interest is growing for novel methods that could help to assess them.

Facades represent a direct means for occupants to control and change the indoor environment thereby providing a significant scope for interaction between occupants and automated or intelligent building components [15]. Historically, occupant interaction with facades has always been crucial in ensuring occupants satisfaction with their level of personal control (e.g. opening a window or drawing a curtain) [16]. The advent of smart materials and automated controls has led to the development of so-called automated, intelligent, adaptive, smart or dynamic facades. These facades can dynamically modify their properties (e.g. modulating thermal or solar energy transmission, air flow and/or daylight) in response to changing indoor demands and outdoor conditions. Intelligent Facades have the potential to improve IEQ levels while reducing building energy use [17]. Examples of such building technologies include switchable and smart glazing, dynamic shading devices or automated operable windows. However, documented case studies show that ill-considered design of occupant interaction with automated facades can lead to poor building performance and low occupant satisfaction [15], [18]–[20]. The reasons for this mismatch between predicted and actual occupant satisfaction with automated buildings facades performance are intrinsically multi-disciplinary [21].

Ongoing research that investigates, and seeks to improve, the interaction between occupants and automated or intelligent facades or buildings is carried out from multiple disciplines, including: automation engineering, building physics, environmental psychology and user experience design. There is a notable lack of comprehensive studies that capture the multi-component and multi-disciplinary complexity of occupant interaction with intelligent facades and automation systems [22]. There is at present no common classification scheme or taxonomy for characterising Occupant-Facade or Occupant-Building interactions across different disciplines. Each of these disciplines has its own set of paradigms, taxonomies and research methods and uses its own discipline-specific terminology. Without a common framework, the generalization of findings on occupant preferences and interactions across multidisciplinary research areas is challenging, and results often remain confined to single discipline domains [22]. Because of this knowledge gap, previous review studies on Occupant-Building or Occupant-Facade interaction have mostly focused on a single components of occupant interaction with intelligent facades or automation systems (Figure 1). For instance, previous works reviewed occupant-centric control strategies for energy performance [5] or thermal comfort [23]. In addition, existing reviews on occupant interaction with facades are typically confined to specific interactions with specific components, such as occupant interaction with windows [24] or with blinds [25].

The aim of this study is to produce a classification scheme that captures the combinations and permutations of Occupant-Facade interactions and investigates different interactive scenarios from the perspective of the occupant. This is achieved by: (i) reviewing existing multi-disciplinary research and consulting with the broader research community to develop the new classification scheme described in Section 2; (ii) Using a carefully selected number of case studies of Occupant-Facade interaction to test and validate the classification scheme as shown in Section 3; (iii) Using the classification scheme to gain new insights on this field of research, discussed in the Section 4, and (iv) draw overarching conclusions in Section 5. The classification scheme proposed in this paper endeavours to facilitate cross-communication of results among different disciplines and provide a novel ground and common language for researchers and practitioners from different fields of expertise.

2 Development of the scheme

2.1 Research boundary definition

The main research focus of this research is the interaction between occupants and façades ("Main research focus" in Figure 2). As shown in Figure 2, the research domain of Occupant-Facade interaction lies at the cross of two wider research boundaries: Occupant-Building Interaction, since facades are a type of building components, and Occupant-Automation System Interaction, since buildings and facades can be controlled by an automation systems. Findings from these two wider research domain can provide useful insights on Occupant-Facade Interaction and, therefore, the following research domain in Figure 2 will also be reviewed: Occupant-Building Interaction, Occupant-Automation system Interaction and Occupant-Automated / Intelligent Building Interaction. The research domain of Occupant-Automated Facade interaction is also included under the research domain of Occupant-Facade interaction, since Automated and Intelligent Facades are a sub-group of Facades and therefore research on occupant interaction with automated facades is also reviewed.

This research paper aims to investigate interaction scenarios from the perspective of occupants in order to provide a classification scheme of the alternative manners in which the occupant can interact with the facades, therefore this review does not include a review of sensing and actuation technologies or of control strategies, which has been previously and respectively done by [26], [5], [27].

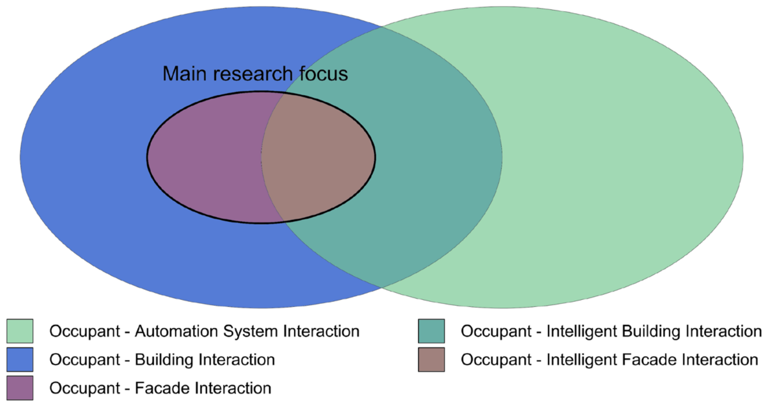


Figure 2 Definition of the main research boundaries

2.2 Existing reviews and classification schemes on occupant interaction with automation systems

The main studies that classify or review occupant interaction with facades or automation systems from a large variety of disciplines are shown in Table 1. Multi-disciplinary research on occupant interaction has mainly focused on understanding occupant behaviour in relation to its effect on energy efficiency [21], [28], [29], while single discipline researches have mainly investigated occupant interaction with individual aspects of automation systems, such as automation level [30] , occupant decision process [31], factors influencing occupant behaviour [24] or occupant-centred control strategies for automated services or facades [5]. Very few aspects have been investigated from more than one discipline, such as the impact of contextual factors on occupant behaviour [26] [34]. Two studies in particular have framed occupant interaction in a multi-discipline perspective, which includes environmental, personal and behavioural aspects: i) D'Oca et al. [21] provides a high-level framework for classifying impactful factors in occupant interaction with buildings; factors are classified under three different domains: environmental, personal and behavioural; within the environmental factors, social and physical factors are evaluated separately; environmental physical factors could potentially include the level of automation and interaction of occupant with intelligent facades or buildings; ii) Von Grabe [33] specifies a larger number of environmental and building factors and provides a preliminary framework that includes both physical (building and environmental), individual and social factors. However, both these multi-discipline frameworks provide a high level understanding and they cannot go into the detail of how alternative interactions affect occupants. Similarly, Occupant-Facade Interactions are not currently regulated by EU standards or guidelines. The only exception is the 2018 revision of the European Energy Performance of Buildings Directive (EPBD) [34], which aims to further promote smart building technologies and establish Smart Readiness Indicator (SRI) for buildings, with a focus on comfort, convenience, wellbeing & health, maintenance & fault prediction and information to occupants. However, the EPBD does not provide guidelines for a satisfactory design of Occupant-Facade interaction.

Several taxonomies also exist in the field of Human-Computer Interaction (HCI) and Computer Science and they provide a detailed classification of different levels of automation [30], but they fail to include any consideration on the effect of automation on occupants. For instance, the concept of Building Operating System has been recently introduced [35], however this framework includes only building managers and interfaces are therefore considered only for providing information on or control over the Operating System. Similarly, in the Building Sciences, Jung and Jazizadeh [27] provided a classification scheme that frames interactive scenarios according the type of control strategy, building and measurement technique, and the performance level of sensing and actuating devices. Although this classification scheme is helpful to frame an interactive scenario within alternative physical characteristics of buildings and devices, the application of this taxonomy remains limited to Building science and does not include any social science aspects, such as occupant response to alternative interactive scenarios or occupant preferred level of interaction. A new comprehensive classification scheme is therefore needed to improve the existing but limited multi-disciplinary frameworks.

Table 1 Main studies that review or classify occupant interaction with automated systems or buildings

Discipline	Aim of the study	Taxonomy or synthesis tool	Ref.	Year
Social Sciences	Understand the decision making process of occupants when interacting with buildings	Cognitive framework for energy-relevant occupant interaction	[31]-[36]	2016-2018
	Understand impactful contextual factors in human interaction with buildings	Data acquisition and analysis method for context of energy	[31]	2016
Environmental Psychology	Improve understanding of how and why occupant interact with buildings	None or not applicable	[37]	2015
Multi-discipline: Social Sciences and Building Physics	Frame occupant behavioural adaptations and building controls to determine impacts on occupant comfort and energy consumption	Multi-disciplinary research framework and survey design procedure	[21]	2017
	Big data for research on household energy consumption behaviours	None or not applicable	[28]	2016
	Review of energy-related behaviours affecting energy use in whole building life cycle	None or not applicable	[29]	2018
Computer Science	Develop a comprehensive building operating system (BOS)	Framework for implementing in one platform all the existing applications	[35]	2013
	Review building automation systems	None or not applicable	[38]	2016
	Review conflict detection methods in building automation systems	Framework for automatic detection of conflicts	[39]	2014
Ergonomics	Classify the levels of automations	8 levels according to the level of automation and intelligence	[30]	2016
Human-Computer interaction	Elucidate occupant activities with augmented objects at home	List of recommendations	[40]	2019
	Review of emotion-oriented requirements of smart buildings	Emotion-oriented requirements for Smart-home systems	[41]	2019
Building Science	Occupant interaction with window blinds	None or not applicable	[25]	2012
	Contextual factors influencing occupant behaviour	Framework for occupant behaviour modelling	[42]	2014
	Methods for in-situ monitoring of occupant behaviours	None or not applicable	[43]	2017
	Driving factors and contextual events influencing occupant behaviour in buildings	None or not applicable	[24]	2017
	Occupancy-based lighting controls	None or not applicable	[44]	2017
	Control strategy for occupant thermal comfort	None or not applicable	[23]	2017
	Occupant-centred control strategy for HVAC	Summary of occupant-centred control strategies to reduce energy use	[5]	2018
	Smart-building sensing system for IEQ	Summary of key sensing technologies	[26]	2019
	Optimised control systems for comfort and energy efficiency in smart buildings	Summary of state-of-art research on optimised controls	[45]	2014
	Classify HVAC operations with occupant in the loop	5-tier taxonomy according: mode of inclusion of occupant in the loop, building type, measurement techniques, sensing performance, HVAC performance	[27]	2019

2.3 Domain selection: main components and interactive scenarios

The main components and interaction mechanisms that form the focus of the current study were identified from common typologies found in literature and through broader discussion with the research community, such as EU COST Action TU1403 "Adaptive Facade Network" [46]. The resulting facade typologies classified in terms of their type and mode of actuation system are shown in Table 2. The typologies range from manually actuated facades to AI-automated facades with increasing levels of sophistication of the actuation system.

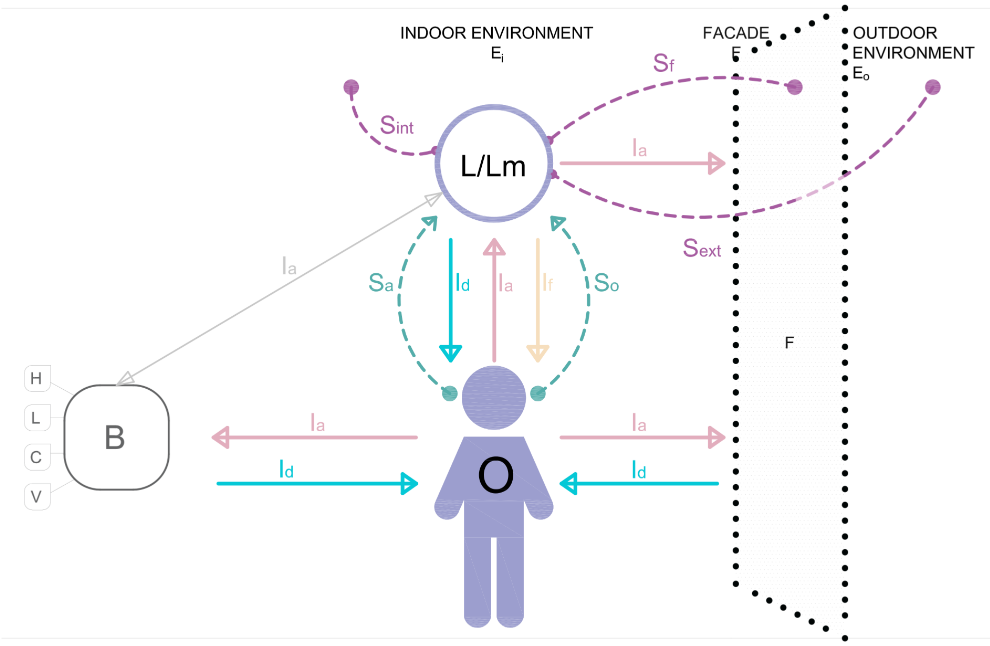
Table 2 Type of facades and actuation system investigated

1. Presence of actuation mechanism	**2. Type of actuation mechanism**	**3. Mode of actuation**	**4. Level of automation of the actuation system**
STATIC No actuation mechanism			
DYNAMIC [47] A minimum of one type of actuation mechanism	SELF-ADJUSTED	Intrinsic material properties [48]	
	MANUAL	Local control [25]	
		Remote control [49]	
	AUTOMATED	Environmental sensing [50]	Rule-based controls [52]
		Occupant-centred [51]	AI-enhanced controls [53]

2.4 Interaction diagram and classification scheme

A new classification scheme was developed by the authors and based on the existing classification schemes described in section 2.1 and it is presented in *Figure 3*. The classification scheme identifies four main physical components: the Occupant (O), as single or group, the control Logic or "Operating system" of the Intelligent Facade and automation system (L), the hardware or physical array of facade components (F) and the Building Services (B). "B" includes artificial lighting, heating, cooling and ventilation management systems. A distinction is made between conventional rule-based Logics (L) and learning ones (L_m), which correspond to automation systems without and with AI-enhanced capabilities respectively.

Each component can interact with the others and create an alternative *interactive scenario.* The interaction is represented by an arrow. The proposed classification scheme identifies two main categories of interaction relatively to their level of intrusiveness and aim: *Direct Interactions* (I) where a *direct* request of action, feedback or information display is made between two physical components, and *Automatic Sensi*ng (S), where there is an *indirect* interaction between two physical components through sensing devices. This notation was then extended in order to sub-classify alternative interactive scenarios found in the review. The following types of Direct Interactions have been identified: 1) Control action I_a; 2) Feedback request I_f; and 3) Display of information I_d. Similarly, the Automatic Sensing was classified according to the aim of the sensing action: sensing of occupants (such as physiological or facial characteristics) S_o or monitoring of occupant adaptive actions S_a; sensing of indoor environment S_i; sensing of outdoor environment S_{ext} and sensing of the facade S_f. The classification scheme proposed can therefore be used to decompose complex Occupant-Facade scenarios into the constituent interactions.



MAIN COMPONENTS

O Occupants
B Building Services (Heating, Lighting, Cooling and Ventilation)
L Logic or control strategy or IT system of the facade
L_m AI enhanced control Logic
F Facade
E_i Indoor Environment
E_o Outdoor Environment

TYPE OF INTERACTIONS

I Direct interaction

- I_a Control Action
- I_f Information request to collect occupant Feedback
- I_d Information Display

S Automatic sensing

- S_a automatic/Indirect sensing of user interactions with the environment for modifying or adapting to it
- S_o automatic/indirect sensing of occupant preference through thermal imaging, facial recognition or physiological sensors
- S_{ext} automatic sensing of external conditions through outdoor sensors or weather station
- S_{int} automatic sensing of indoor condition through indoor sensor
- S_f automatic sensing of facade

Figure 3 Interaction diagram and classification scheme of occupant facade interaction

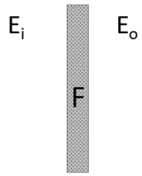
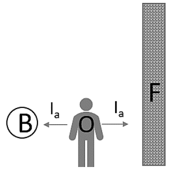
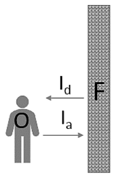
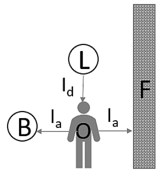
3 Validation of the scheme for different interactive scenarios

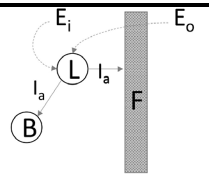
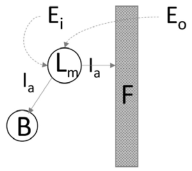
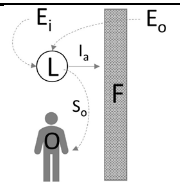
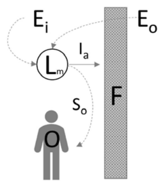
The classification scheme was validated, by testing it on intelligent facades found in real world and theoretical case studies. The case studies were selected based on the authors' experience and, subsequently, their discussions with the broader research community, namely the Working Group 3 (WG3) of the EU COST Action TU1403 "Adaptive Facade Network" [46]. Several key-words were then chosen to continue the research in online scientific research databases and a broad review was conducted to identify studies on intelligent facades. More information on the literature review methodology is presented in the Appendix A.

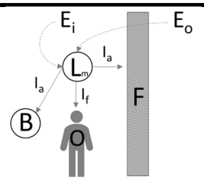
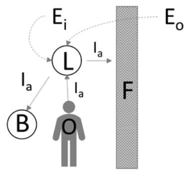
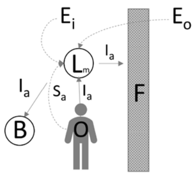
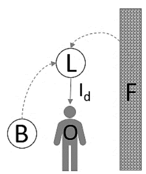
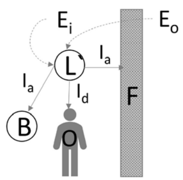
The classification scheme was applied to each case study and results from this validation are reported in *Table 3*. Case studies, which are grouped according their characteristic interactive scenario indicated in *Table 2,* and the main references are reported in *Table 3*.

3.1 Classification of case-studies according the proposed scheme

Table 3. Review of available interactive scenarios according to the classification scheme, description and examples and main references.

Facade type	Name of the interactive scenario	Pictogram of the Interactive scenario	Description and examples	Main references
Dynamic Self-Adjusting Facade	$E_{i/o}$ F		Self-adjusting facades: the adjustment is triggered by outdoor conditions without need for any Logic. Example: thermochromic , phase change materials, homeostatic facades etc.	• Review [48], [54]–[56]
Dynamic Facade with Direct Interaction – no control Logic	O I_a F O I_a B		The occupant operates the facade manually or through dedicated interfaces. Examples: -Operable windows. Facades with indoor manual shading devices. -Facades with remotely controllable shading devices such as switches, remote controllers or web-based applications. Artificial lighting and/or HVAC systems with switches or remote controllers.	• Case studies -Occupants manually operate shading devices: [49], [57]–[65] -Occupants manually open windows [66] -Remotely-controlled Facade [49], [67] • Review [24], [25], [58], [68], [69]
	O I_a F F I_d O		The occupant commands the facade to display information and receives information from it. Example: Media Facades	• Facades [70], [71]
	L I_d O ; O I_a F L I_d O ; O I_a B		The logic directly conveys information to occupants to suggest control actions. Example: Window signalling systems or eco-feedback systems for HVAC and lighting services.	• Building Services [72]–[77] • Facades [78], [79]

Facade type	Name of the interactive scenario	Pictogram of the Interactive scenario	Description and examples	Main references
Dynamic Facade Logic with Environmental sensing, no Occupant Interaction	$S_{e/i}$ L I_a F $S_{e/i}$ L I_a B		The logic is informed from the sensing of indoor and outdoor conditions and controls the facade accordingly. Example: conventional automation systems for facades e.g. automated shadings that are based on outdoor or indoor sensors.	• Facades [80]–[88] • Building Services and Facades [89], [90] • Reviews [50], [91]
	$S_{e/i}$ L_m I_a F $S_{e/i}$ L_m I_aB		The logic is informed from the sensing of indoor and outdoor conditions and controls the facade accordingly. The logic can also learn and predict future weather conditions and optimise the facade control strategy. Example: Automated Facades with predictive control strategies.	• Review [92], [93] • Facades [50], [84], [94]–[96] • Building Services [97]–[99] • Facades and Building Services [100], [101]
Dynamic Facade Logic with Automated Sensing of Occupants	$S_{e/i//o}$ L I_a F $S_{e/i//o}$ L I_a B		The logic senses from the occupant and accordingly operates the facade or Building Services actuator in real time. Example: Real-time response of Building Services to occupancy,	• Real-time activity recognition for services [102] • Real-time affective sensing for facades [103] • Reviews: Occupancy based services [44]
	$S_{e/i/o}$ L_m I_a F $S_{e/i//o}$ L I_a B		The logic senses from the occupant and accordingly operates the facade or building services actuator, learning in time from occupant data. Example: Real-time and learning occupancy recognition systems,	• Building Services – Occupancy [104]–[106] • Building Services and real-time sensing of occupant comfort [107]–[112]

Facade type	Name of the interactive scenario	Pictogram of the Interactive scenario	Description and examples	Main references
Dynamic Facade Logic with Direct occupant Interaction	$S_{e/i}$ L_m I_f O ; $L_m I_a F$ $S_{e/i}$ L_m I_f O ; $L_m I_a B$		The logic reads the indoor and outdoor environment and elicits occupants for direct feedback, then adjusts the facade or the Building Services and learns to predict occupant feedback. Example: Automated facades with occupant feedback from web-based applications or mobile apps	• Building Services [106], [113]–[119] • Facades [60], [120]–[122]
	$S_{e/i}LI_a$ F O I_a F $S_{e/i}LI_a$ B O I_a B		The logic is informed from the sensing of indoor and outdoor conditions and controls the facade accordingly. However, occupants can override the automation system for a time interval. Example: Commercially available automated facades such as Electrochromic glazing or Automated Venetian Blinds, and Automated HVAC or Artificial lighting systems.	• Automated blinds [13], [18], [123]–[126] • Services [127] • Switchable glazing [128] • Through voice commands - Building Services [72] • Through Gesture Elicitation – Facades [128]–[130]
	$S_{e/i}$ LI_aF OI_aF $S_aL_mI_aF$ $S_{e/i}$ LI_aB OI_aF $S_aL_mI_aB$		The logic is informed from the sensing of indoor and outdoor conditions and controls the facade accordingly. However, occupants can override the automation system, which is learning from occupant overrides. Example: Self-adaptive integrated control of automated blind facades	• Facades [131], [132] • Building Services [53], [133]–[135] • Building Services and Facades [136]
	S_f L I_d O S_b L I_d O		The logic conveys information on the actuator performance to the occupant. Examples: Logics that automatically conveys information on actuator failures of Building Services or facades.	• Building Services [137] • Facades [130]
	S_i L I_a F ; L I_d O S_i L I_a B ; L I_d O		The logic conveys information to the occupant on the automation strategies, which are based on indoor or outdoor data, in order to increase occupant acceptance of automated controls. Example: Automated blinds with light feedback	• Building Services [72], [73], [135], [138], [139] • Facades [123], [137]

4 Insights gained from Classification Scheme

4.1 Characteristics of each interaction class and future research needs

Table 3 groups the results of the literature review according the proposed classification scheme. This arrangement is useful to: i) clarify relationships between main components; ii) highlight the characteristics of each interactive scenario and similarities between alternative scenarios, and iii) identify future research needs for each type of interactive scenario. The classification scheme captures and represents the large number and distinct types of interactions encountered in the case studies. Case studies under the same group of interactive scenario in *Table 3* reported similar characteristics that were then summarised in *Table 4* as: i) the advantages and disadvantages of each interaction, ii) the triggers of occupant satisfaction for each class of interaction, iii) contextual factors affecting occupant satisfaction, and iv) research gaps. From *Table 4* the following insights are drawn:

- **There are no general and universal design solutions for satisfactory interaction strategies:**

The large number of contextual factors listed in *Table 4* shows that design principles for satisfactory interaction scenarios are difficult to be generalised. Satisfactory levels of interaction require bespoke design solutions, which consider both local occupant expectations and background or other contextual factors such as building typology. Therefore, flexible or adaptive solutions that could be tailored to case by case scenarios and ensure high level of personalisation are required.

- **The holistic effects of interactive scenarios on occupant satisfaction are yet to be fully-captured:** The research gaps reported in *Table 4* highlight the need for more research on the holistic effect of interactions on occupants. Methods from Human-Computer Interaction and Human-Building Interaction could help designers to meet these new demands [140]. In the design stage, the use of "Personas" and techniques for mapping the spatial context of interaction identify means to improve usability [141]. When prototypes are available, the use of task analysis, interviews and focus groups could be useful tools to assess occupant response to them. When prototypes are not available, virtual reality and novel computational design classification schemes [142] could be used to assess occupant response to novel interactive systems. Several methods could be used to investigate occupant response in alternative interactive scenarios, such as video recording, monitoring physiological responses [143] and eye movement [144].

- **Interfaces play a key role in ensuring occupant satisfaction with interaction strategies:**

A well-considered design of interfaces is widely recognised by existing research as a key trigger of Occupant satisfaction in many type of Interaction strategies (*Table 4)*. More interdisciplinary research is here needed to define the concept of ease-of-use and to improve both the functional and psychosocial fit with the user [141]. The level and mode of interaction should vary with the context, user and function. Krukar et al. [140] have already tried to extend the concept of "Usability" from HCI studies, redefining it as "user experience", which better embraces the large number or occupant needs when interacting with Intelligent facades. Use of novel interfaces in the built environment is still underdeveloped. Research on wearable technologies and affective human-computer interaction provides several options of novel interface design [145]. Facial expressions can be used to detect levels of emotions [145], [146] or environmental satisfaction in a contact-less manner, however they may not always be detectable [147]. Cosma and Simha [148] suggested that just one arm could be a sufficient indicator of thermal sensations, while Li et al. [149] and Ghahramani et al. [112] focused on facial skin temperature as a useful bio-signal for comfort preferences. Several other studies have investigated physiological signals such as heart rate for environmental control [149], [150], or peripheral temperature and skin conductivity for emotion or comfort detection [151]–[153]. Brain to computer interfaces, such as electroencephalographic (EEG) signals, have also the potential of disclosing large amount of information on occupants [147], [154], [155], brain monitoring has the risk to become too invasive for environmental control strategies in ordinary daily basis.

- **Interactive strategies have ethical and privacy consequences that need to be addressed**:

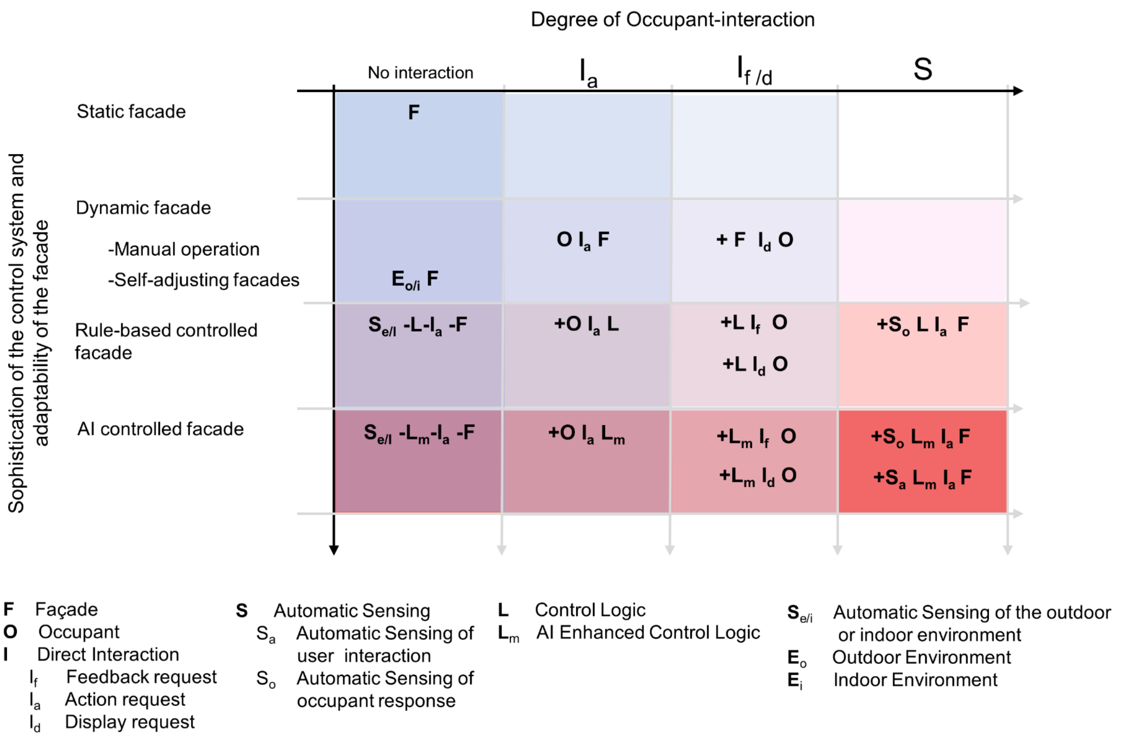
All the Automatic Sensing interactions in *Table 4* report issues related to ethics, privacy, surveillance and datafication, especially when large datasets are collected on individual preferences [156], physiological responses and mood, productivity or well-being conditions. Ethical concerns have led to the development of new governmental guidelines [157] and the current wealth of research that attempts to address such ethical concerns. As pointed out by Cascone [158], main concerns are related to: 1) ensuring occupant awareness and permission in collecting such data; 2) protecting personal data in safe storages; 3) limiting accessibility to the data to not authorised personnel and breaching of confidential data. Consequently, the development of new effective methods for not-intrusive occupant data collection will have to face ethical challenges and more research is needed to answer the new ethical questions, opened by an "unprecedent degree of intimacy" between occupants and automation controls [159]. In this sense, a clear understanding of the benefits and advantages of embedded computing in buildings would be needed to override and outweigh potential privacy and security disadvantages [160].

Table 4 Summary of the characteristics of each class of interaction, drivers of occupant satisfaction and future research needs

Interaction	Advantages	Disadvantages	Triggers of Occupant satisfaction	Contextual factors affecting satisfaction	Research gap
I_a Control Action	• Give occupants personal control [161] • Allow users to override automated strategies • Increases user acceptance of logic [15], [162][163] • Provides data on overrides which can be used to train Logic [1]	Potential detrimental effect on energy performance of automated systems [164] Manually controlled systems often remain in switched state [49], [53]	-Level and type of perceived control [13], [15], [165] -Interface design [163]	-User background [137] -User expectations of level of control [63] -Effectiveness and Efficiency of interface [165] -Location e.g. Distance from facade [15], [166] -Number of occupants [69], [166], [167] -Space layout [58], [167], [168] -Time of day, season and weather [57], [65]	-Deliver methodologies that tailor level and type of perceived control to occupant needs case by case [15], [163] -Identify the balance between automated control and occupant overriding case by case [169] -Capture the holistic effect of control interfaces -Investigate novel interfaces such as vocal commands [72] or gestures [128]
I_f Feedback request	• Gather data on actual occupant preferences [1]	Potentially Disruptive to occupant activities [1] Sensitive to interface design [170]	-Interface design [114] -Frequency of interaction [1]	-User background [170]	-Need for novel methods / interfaces to gather feedback data with sufficient level of spatial and temporal granularity without being disruptive [1] -Improve consistency between user expectation and comfort votes [170]
I_d Information display	• Communicate to occupants information on environmental and building conditions [171] • Suggest occupants control actions [78] • Communicate the rationale behind the logic and increasing acceptance of control strategies [172] • Enhance energy efficient behaviours of occupants [73]	Potentially Disruptive to occupant activities [173] Sensitive to interface design [171]	-Interface design	-Notation and language [113] -User background and expectations	-Limiting overcomplexity [173]
S_a Sensing of occupant interaction	• Not disruptive manner of understanding occupant preferences	Ethical and privacy implications [158] Context and activity dependent: space layout, building characteristics, type of building [25]	-Clear communication that occupant behaviour is monitored [160]	-User background and expectations	-Understand better holistic triggers of occupant satisfaction -Understand motivation behind occupant actions [25] -Overcome context dependency [57] -Rules for protecting occupant privacy [160]
S_o Sensing of occupant preferences	• Not disruptive manner of understanding occupant preferences • Potential to gather high-frequency personalised data on occupant preferences	Ethical and privacy implications [158] Potential to be too intrusive [145] Highly dependent on personal and contextual factors	-User acceptance of the sensing interface	-User background and expectations [145]	-Understand better holistic triggers of occupant satisfaction -Develop more effective sensing devices -Need for more data to correlate actual occupant preferences with biometric or physiological data

4.2 Towards a desired interaction strategy

The interactive scenarios described by *Figure 3* and shown in *Table 3* present a broad range of alternative levels of control Logic and occupant-centred data. Figure 4 shows the range of possible interactive scenarios according the level of Sophistication of the Logic and the adaptability of the facade (as described in *Table 2*) and the degree of Occupant Interaction with the system. The Occupant-Facade scenarios shown in *Table 3* can be ranked in terms of increasing level of occupant interaction. The first scenario on the left is characterised by the absence of interactions between Occupants and Logic. Moving along the x axis, the level of interaction increases. In scenarios with only control actions I_s, occupant can either manually operate the facade or just override automated strategies. In scenarios with feedback I_f or display request I_d users can also explicitly express their preference or receive information. Lastly, occupant preferences are automatically sensed by the Logic in S type interactions. In this sense, the interactive scenarios located at the right bottom corner of Figure 4 are characterised by high level of personalisation, since they present many types and levels of occupant interaction. These interactive scenarios also have the potential of maintaining high levels of energy efficiency due to the Intelligence of the control strategy and the adaptability of the facade. Increasing levels of sophistication of the control logic and adaptability of the facade advocate the idea of control strategies as "butlers" that suggest [174] environmental changes rather than strictly control the environment.



1

Figure 4 Intelligence of the control systems versus level of occupant interaction in the interactive scenarios classified in Table 3. The interaction scenarios are defined in Table 3.

The degree of Occupant interaction and Sophistication of the Logic-Facade system could also be adjusted at different stages of the building life [175]. Levels of automatic control could gradually increase together, and in parallel, with their user acceptance. In this sense, Ball and Callaghan [175] reported a user evaluation of an "adjustable autonomy system", whose levels of control were gradually increased, as the user gained confidence with the interactive system. In doing so, an interaction strategy as part of the learning process could progressively move towards the lower parts of the graph in Figure 4, becoming more "assertive" and having the potential of gradually optimising energy efficiency whilst maintaining high levels of occupant acceptance.

The emphasis goes then on entrusting users with the appropriate levels of perceived control and types of interaction in time, as presented in the classification scheme. The design of Occupant-Facade interaction should select the interaction strategy (e.g. Control action, Display request, Feedback request or Automatic Sensing) according its "effectiveness" [165] and deliver the most appropriate one [166], rather than just providing a large number of possible interactions Eventually, a special emphasis should be on the "required degree of responsiveness" to achieve a satisfactory user-facade interaction, considering that significant individual differences exist between occupants [20] and effects of the control domain of facades.

The Logic could also be designed focusing on the "personality" that users tend to attribute to control systems [72], since levels of automation or personal control are perceived by occupants accordingly to "personality" features. Low levels of automation have been previously perceived by users as less 'extravert and open' than systems with a "medium level of automation", which were also considered to be more "emotionally stable and agreeable" [137].

5 Conclusion

Artificial intelligence and a new generation of interfaces have the potential to enhance occupant interaction with intelligent buildings and facades, creating new interactive scenarios where occupants are connected with control loops, providing human-centred solutions. The advent of these technologies is expanding the notion of personal control: intelligent buildings do not allow occupants to just control the environment, but also to condition it with their preferred levels of daylight, thermal qualities and other environmental characteristics. However, effective interaction strategies where occupants are able to communicate the whole extent of their multisensorial experience to the Logic are yet to be achieved.

Designing for satisfactory user interaction requires multi-disciplinary approaches, which would benefit from a comprehensive classification scheme that enables cross-communication between different fields of expertise. This paper reviews previous multi-discipline taxonomies in the built environment in order to provide a common classification scheme for practitioners and researchers working on Occupant Interaction with Intelligent Facades. The proposed classification scheme consists of an interaction diagram and an associated taxonomy notation that can be used to communicate across different disciplines. The new classification scheme captures the multidisciplinary nature of Occupant-Facade interaction and it can therefore be used to communicate findings across disciplines. The classification scheme helps to clarify relationships between main components and to arrange the interactions between occupants and facades in groups, according their similarities and characteristics. From this, it was found that there are two main type of Interactive scenarios: Action Interaction and Automatic Sensing. A summary of the characteristics of each type of interaction is shown in this paper. However, future work will need to investigate these interactive scenarios in relation to cost, complexity and reliability in order to inform optimal design solutions for Occupant - Facade interaction. These interactions are highly case-specific and time-varying, depending on the facade and logic typology, building design and occupant needs. Therefore, universal solutions and generic design guidelines are difficult to be achieved.

The proposed scheme aims to capture the combinations and permutations of Occupant-Facade interactions and, hence, only partially includes Building Services. More research is therefore needed to include the effect of occupant interaction with other building components. Moreover, this paper evaluates only the effect of interactive scenarios on occupant satisfaction, which is only one aspect of the multi-domain requirements of occupant-centric smart buildings. For a well-considered occupant-centric design and operation of smart buildings, this scheme needs to be used in combination with the existing frameworks that aims to capture the wider effects of smart buildings on occupants, such as wellbeing & health or ease of maintenance and efficiency of smart building components.

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Appendix A

The literature review was performed using the following search engines: Science Direct, Google Scholar and Taylor and Francis. The following list of keywords was used:

Occupant AND interaction AND façade
User AND Interaction AND Buildings
Personal control AND Automation AND Building
Human comfort AND Automation
Automatic AND Sensing AND Occupants
Automated Blinds AND Comfort
Automated Blinds AND Occupant AND Interaction
Automated Blinds AND Interaction
Automated AND Occupant AND Feedback
Window AND Occupant AND Feedback
Window AND Occupant AND Feedback
Window AND User AND Feedback
Control strategies AND facade AND Override
Switchable glazing AND Occupant AND Interaction
Facade AND Communication AND performance
Envelope AND Communication AND performance
Facade AND Information AND Performance
Facade AND Computer in Human Interaction
Building Intelligence AND Occupant Behaviour
Information AND Occupant AND Envelope
IoT AND Buildings AND Comfort

The collected papers were analysed during the three years of the COST Action TU1403. The final selection of paper was performed: i) reading the full papers ii) selecting only the ones containing information related to the aim of the review.

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