

Impacts of Human Energy-Related Behaviours on the Energy Efficiency of Adaptive Building Façade

A Review

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Amid growing imperatives for heightened building energy efficiency and occupant comfort, adaptive façades have garnered significant attention and research efforts aimed at refining their structure and techniques to achieve energy savings. However, studies frequently overlook the consideration of human factors that impact the energy performance of adaptive façades, with limited discussions on potential solutions. In this review study, an investigation is undertaken to firstly delineate the challenges posed by occupant disruptive behaviour to the expectation of adaptive façade operations. Secondly, this study focuses on reviewing gamification design and implementation techniques aimed at enhancing operational efficiency and fostering increased user engagement. Findings from this review indicate that occupant-oriented adaptivity is crucial for the effective operation of adaptive façades, underscoring the importance of incorporating occupant-empowered control when automation systems are involved. Furthermore, the review highlights the necessity for gamification implementation methods to align with the unique characteristics of the building type and its occupants. Particularly, achieving a balance between extrinsic and intrinsic motivation appears as crucial. This study serves as a foundational resource for researchers and practitioners seeking to leverage the gamification for enhancing data communication and collection by promoting users' engagement and positive behavioural change within the context of building adaptive façades - users interaction.

Keywords: *adaptive façade, building energy efficiency, human factors, occupant energy behaviour, gamification.*

INTRODUCTION

Amidst the escalating threat of the greenhouse effect, urgent measures demand the reduction of carbon emissions to zero across all sectors by 2050, particularly in the building construction and operation sector, which the energy demand in the building's operation constitutes approximately

30% of the global final energy consumption (IEA, 2023), including necessities such as heating, cooling, lighting, ventilation, and appliances. The cumulative energy consumption within the buildings sector has demonstrated an average annual increase of 1% over the preceding decade.

Significant investments towards improving energy efficiency have already made in the improvement of building envelope elements, automation and control, sensing infrastructures for relevant data provision, and total or partial exchange of energy source. Especially, adaptive building façades have the potential to improve indoor environment quality, diminish building energy consumption, and sustain or elevate user satisfaction (Romano et al., 2018). However, the market penetration of adaptive façades (AFs) is far from sufficient, with less than 5% of the European market and less than 1% of the UK market, even though their capabilities have been recognized in research. This is because, limited existing adaptive facades in the market is susceptible to disruptions caused by user overrides and external control of the façade system. This disruption often leads to suboptimal energy utilisation.

As human factor starts playing an important roles in energy efficiency within adaptive façade systems, previous research has worked on control techniques, response features, and interaction activities to avoid occupant disruption or at least minimise occupant override behaviour (Tabadkani et al., 2021). However, preprogrammed stimulate-response façade system is challenging to meeting the diverse end of user. Based on the massive user behaviours issues, limited studies have showed some potential by using advanced algorithm to learn different users' preference (Shi and Pouramini, 2022), or applying gamification strategy to promote users' engagement (Paris et al., 2019). Rather than avoiding human involvement, accepting human engagement as a massive user data to analysis and optimise façade performance to give a suitable response and adapt to surrounding dynamic environment is the new concept to support the adaptive façade development. However, no extant literature study has approach building façade from a gamification perspective. Thus, it becomes imperative to elucidate the current status and future

developmental trends regarding the gamification approaches and their impacts on the energy use and users' energy-related behaviours in buildings.

Given the identified research gaps, this literature review seeks to expose the main challenges stemming from human factors in the implementation and operation of adaptive façades. Subsequent to identifying the challenges hindering adaptive façades in achieving energy efficiency goals, the review will examine gamification techniques aimed at resolving the conflicts between occupant satisfaction and energy conservation within the context of adaptive building façades.

METHODOLOGY

This review study will be conducted in two phases. Firstly, it will integrate theoretical-based paper analysis with practical-based real case studies, structured interactively as depicted in (Figure 1), Secondly, to explore the influence of gamification strategy on human behaviours, bibliometric mapping will be employed to initially provide an overview of the gamification research network in building energy efficiency. This will be followed by a detailed analysis of selected relevant literatures. This approach aims to facilitate a review of gamification strategies concerning user energy consumption-related behaviours.

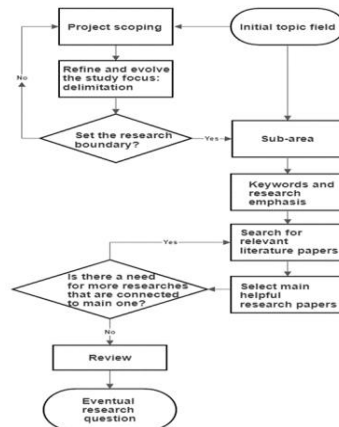


Figure 1
An interaction
process of
literature review
on occupant-
façade interaction.

In the analytical framework shown in the top left corner of figure 1, the Python data programming language and the Jupyter coding environment are utilized alongside Biopython and Elsaply libraries to access publications from established literature databases, including Scopus, Web of Science (WoS), and Google Scholar. Specifically targeting abstracts relevant to the search term "adaptive facade – occupant interaction," the Panda and Matplotlib libraries are employed to extract, clean, and organize publication data into a data-frame, which is subsequently sorted for visualization.

This methodological approach enables the identification of the community pulse, research core, and pivotal contributors within the respective scholarly domain, thereby offering valuable insights to inform the direction of the literature review. Furthermore, data pertaining to occupant- adaptive façade interaction is extracted from WoS, converted into a text format, and subsequently inputted into VOSviewer software to generate a density visualization, elucidating the distribution and prominence of associated keywords within this research realm. Such visual representations serve as foundational tools for discerning prevailing themes and potential trajectories for further investigation.

Furthermore, employing a keyword-driven search mechanism across the aforementioned databases, aligned with the predetermined research emphasis of this study, facilitates the identification of seminal research endeavours. Among these, 28 case studies concerning adaptive façade applications in literature are selected for comparative analysis, aiming to elucidate differences across diverse characteristics of adaptive façades.

Following the delineation of human impacts on adaptive façade operation and performance through the identified research work analysis, a preliminary investigation into gamification literature commenced. The initial search was conducted using the keywords "Gamification,"

"Users," "Energy Efficiency," and "Buildings". This search yielded a total of 1645 research articles. For the purposes of the present study, research articles were sourced from primary databases, including Web of Science, Scopus, Science Direct, Springer Link, and IEEE, with a focus on journal articles and review articles. Subsequently, out of the initially identified 1603 research studies, 306 studies were discerned as directly pertinent to the objectives of this review.

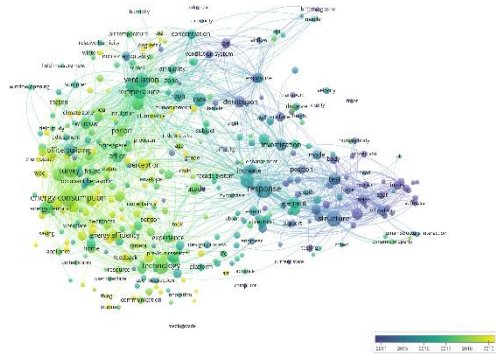
The research studies selected for the review were obtained based on the inclusion criteria that include four facets: 1) Studies that present gamification solutions designed to engage users in specific energy-saving activities; 2) Analyses focusing on gamified systems aimed at motivating users to adopt energy consumption-related behaviour changes; 3) Studies utilizing gamification approaches within building systems or components to facilitate user interactions and gather user preference data. Excluded from this review analysis were the research works that: 1) Do not incorporate gamification within the context of buildings; 2) Investigate gamification in building systems without providing analyses of user engagement.

This overall selection process yielded a final set of 21 principal articles from the initial pool of 306 identified studies. The chosen studies have been classified into four categories: 1) Gamified systems and the platform; 2) Elements of gamifying process for user engagement; 3) Gamification solutions impacting users' energy consumption-related behaviour change and 4) Effects of gamification application on building energy efficiency.

RESULTS ANALYSIS

In the exploration of weak links within the literature concerning occupant-adaptive façade interactions, a network map representing the evolution of research trends over time is generated using VOSviewer, providing an initial

overview of the dynamic façade – occupant interaction landscape, see figure 2.



In figure 2, the timeline depicts the progression of mainstream topics in the field's development, beginning with Structure and moving to Responsive functionality, then the Performance of Ventilation and Temperature, and finally Energy Consumption and Technology enabled applications and developments, with a focus on user involvement. Specifically, there is a dense network of communications surrounding the three primary points of Response, Ventilation, Temperature, and Energy Consumption, with numerous branching points around each issue. The central point of the topic of Technology, in contrast, has a sparse network of connections surrounding it, with a very limited number of branch points associated with it, as well as relatively few branch points related to other topics.

Given the observed disparity in connectivity between the technology cluster and the energy consumption cluster, particular attention is directed towards the technical attributes inherent in adaptive façade functionalities. To facilitate this investigation, 28 case examples of adapted facades was selected from literatures. An overview matrix outlining characterization concepts pertinent to envelope response capabilities was updated, see figure 3.

Subsequent analyses were conducted to delineate the contemporary status of adaptive performance exhibited by building envelopes in practical scenarios, along with insights into their interactive functionalities with humans, particularly with regard to enhancing energy efficiency.

The analysis of the 28 selected case studies unveils two significant issues pertinent to human factors within the scope of this investigation: 1) Limited Interaction Capabilities: adaptive façade implementations are observed to be triggered and modulated by factors such as temperature and view dynamics (Attia, 2019). Notably, the typology of buildings featuring adaptive façades predominantly comprises commercial office and residential structures, designed to serve the needs of users and occupants. However, the investigated adaptive façades primarily demonstrate a climate-oriented response, predominantly catering to weather conditions and settings of indoor environmental quality, rather than directly addressing user behaviours; 2) User-empowered adaptive façade: A preference is observed for dynamic façade endowed with adaptive capabilities capable of delivering personalized responses in fully automated responsive façades. Particularly, intrinsic systems, wherein material properties adapt to environmental conditions without direct response to human stimuli, are more commonly employed in operational systems compared to extrinsic systems, which incorporate programmed mechanisms for automated weather-responsive adjustments. Recent post-occupancy research by (Attia, 2019) suggests that occupants anticipate encountering intelligent technology capable of anticipating their needs and delivering effective responses. However, while occupants value the automated adaptation offered by fully automated façades, they also express a desire for manual control, allowing for manual adjustments when necessary, even within automated systems.

Figure 2
Adaptive façade-
occupant network
visualization
through the
timeline in
VOSviewer.

Figure 3
Overview matrix of characterization concepts for dynamic façade response ability (with updated contents from (Aelenei et al., 2018; Tabadkani et al., 2021)).

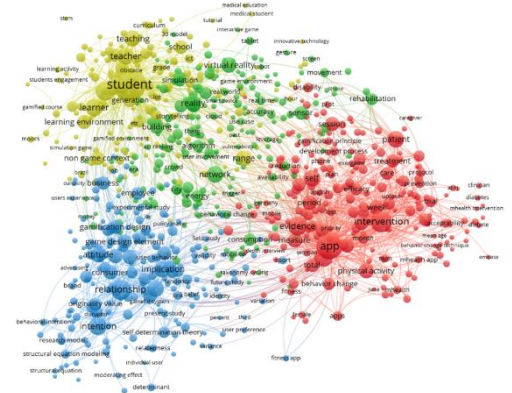
Purpose	Responsive function	Operation system	Component (materials and systems)	Responsive time	Spatial scale	Visibility	Degree of adaptability	Actuation mechanism	Movements	Control type of the elements
Thermal comfort	Prevent	Intrinsic (passive)	Shading	Seconds	Building material	No/low	On-off	Manual (Self-adjusting / user override)	Full rotation	Individually
Visual comfort			Insulation	Minutes	Facade element					
IAQ	Reject	Extrinsic (active)	Invisible glazing	Hours	Wall	Medium	Gradual	Automated (environmental sensing, occupant-centred)	Deforming	Total movements
Acoustic performance	Modulate		PCM	Day	Window				Folding	
Personal control and interaction	Collect		SMA	Seasons	Roof	High			Sliding	
Energy performance			SoC	Whole building	Hybrid					
Appearance			Solar system							
Humidity comfort										

The challenges delineated in the case studies of adaptive façades highlight the critical influence of human factors on energy efficiency outcomes. This circumstance impedes the acquisition of precise and relevant data from occupants, which is indispensable for optimizing the operational energy performance of adaptive façades. Consequently, there is a pressing need to motivate occupants to actively engage in building energy-saving initiatives.

Figure 4
Overview of gamification research network in building energy efficiency.

In the domain of incentivizing occupants' behaviour, gamification emerges as a considerable strategy. It involves the application of game-design elements into non-game environments to augment user engagement, motivation, and behavioural transformation outcomes (Deterding et al., 2011). As gamification is a relatively new concept which starts gaining more attentions for connecting, collaborating, and interacting with consumers, educators, and medical partners in the areas of business market development, online learning, and medical treatment since the last decade, key theoretical understandings are still emerging. Figure 4 shows that gamification has exhibited noticeable achievement in design methodologies, techniques, and influence, with limited emphasis on user typology or practical applications. Specially, the impact of gamification remains constrained by its association with a singular user group, primarily in the field of education, as

evidenced by the prominence of the keywords related to teacher and student within the yellow cluster. The intersections between user and gamification design techniques require additional refining from a practical viewpoint.



The literature reveals seven implementation techniques, namely Human Machine Interface (HMI), Apps, Internet of Things (IoT) based, Web-based gamified systems, software, Information and Communication Technologies (ICT) platform, and Graphical User Interface (GUI), as identified by the principal studies selected for this review (Iria et al., 2020). The radar chart below (figure 5) gathers data from chosen relevant literature on various gamification techniques based on the building type. In terms of total usage, Apps and

HMI stand out in residential and higher education, occupying first and second position, respectively, while software and GUI are barely utilised.

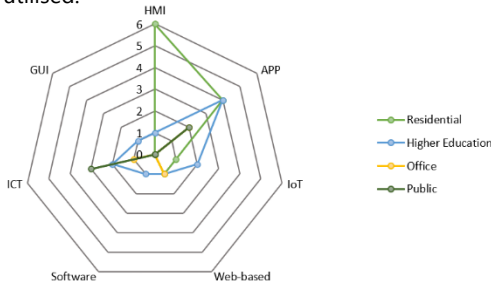


Figure 5
The distribution of gamification techniques in various building types.

A decision matrix is used to show the characteristics of pros and cons among seven implementation techniques in terms of human-centric, data-driven, and convergence perspectives (figure 6) based on the selected studies. The assignment of weight to each criterion in the table reflects its relative significance in the decision-making process, (where 1 denotes low, 2 signifies medium, and 3 conveys high importance).

	User-friendliness	Data collection	Data analysis	Real-time control	Accessibility	Customization	Integration	Score
HMI	3	2	2	3	2	3	3	18
App	3	3	2	2	3	3	3	19
IoT	1	3	3	3	2	2	2	16
Web-based	2	2	3	2	1	3	3	16
Software	2	2	2	3	1	3	2	15
ICT	1	3	2	3	3	2	2	16
GUI	2	2	1	2	2	3	3	15

As can be seen in figure 6, among the 7 different gamification implementation techniques, the App achieved the greatest score, while the GUI and software had the lowest and most limited utilisation in the existing research. For a diverse user base, Apps provide mobility and portability, as they are easily accessible on mobile devices such as smart phone, tablets, and smartwatches, facilitating engagement through various gamification components (Paris et al., 2019). Significantly, Apps can be developed

across diverse construction contexts. In environments including both public and mixed-use structures (e.g., commercial and residential), HMI provides real-time control and is favourable for monitoring and operating machines and systems. GUI enhances user-friendliness and accessibility, thereby supporting user engagement through the interface design, particularly suited for deployment in office, higher education, and public buildings. IoT contributes to automation and energy management by supplying data for gamified systems. ICT facilitates data sharing and collaboration, supporting the integration of gamification features. Both IoT and ICT are applicable to various building types, especially smart buildings (Mendez et al., 2021). However, the utilization of Software is primarily constrained by the considerable time and cost requirements associated with development and maintenance. Web-based gamified systems, while offering cross-device compatibility, garner comparatively less attention than apps or other intelligent screen or touchable interfaces.

In addition to assessing the performance attributes of various gamification techniques, the integration of gamifying elements within building systems necessitates careful consideration of the target platform. The selection of relevant gamification elements holds paramount importance in meeting project objectives and satisfying end-users. Reward serves as a fundamental element in gamification initiation, irrespective of the utilized implementation method. Typical rewards include points, badges, coupons, and discounts, as they offer tangible benefits to users. In terms of popularity, these elements are followed by feedback, dashboard, and social message (Gangoells et al., 2021). Figure 7 present the characteristics and evaluations of different integration platforms showed in selected literatures among the 7 gamification techniques. The platforms used to integrate with gamified systems within building

Figure 6
Decision matrix for 7 gamification implementation techniques.

contexts are classified into 3 directions. These directions include groups related to energy acquisition and dissipation, such as thermostats, photovoltaics (PV), and Heating, Ventilation, and Air Conditioning (HVAC) systems; energy monitoring group, including smart meters, sensors, and plugs; and notably, the least prevalent application platform identified in this synthesis is the computer (Iria et al., 2020). Furthermore, the effectiveness of different gamification design elements in optimizing resource utilization and energy consumption was also investigated across various implementation techniques, with results detailed in figure 7.

Figure 7
Characteristic and evaluation of each platform gamified system within buildings.

Techniques	Target Interface	Gamification Elements	Resource Utilization	Energy Consumption savings
HMI	Thermostat, PV, HVAC	Points, Feedback, Competition, Dashboard, Statistics	Control, monitoring	15% [38]
App	Thermostat, PV, smart meters, smart plugs, sensors, HVAC	Feedback, Points, Challenges, Dashboard, Statistics, Leaderboard	Get user engage in resource interconnection	20% [26]
IoT	Smart meters, Plugs, Sensors	Competition, Point	Enable real-time automation and data-driven decisions	40% [50]
Web-based	Computer	Points, Competition, Feedback, Leaderboard, Cooperation	Media and social network to support user engagement	10% [43]
Software	Computer	Point	Customization with optimise resource utilization	8% [44]
ICT	Lighting, HVAC, Meters, Plugs	Point, Dashboard, Feedback, Competition, Social	Data exchange, communication, and collaboration	15%-30% [46]
GUI	Sensors, Meters	Point, Dashboard	Visualization, easy to understand	40% [32]

In accordance with the illustrated details in figure 7, Points represent a crucial element of gamification, serving as a direct motivational tool to engage users and stimulate their involvement in energy-related behaviours. Within the platform of thermostats, HVAC systems, and photovoltaics (PV), the incorporation of gamification design elements assumes paramount significance, enabling users to dynamically manipulate and monitor energy dynamics in real-time. Gamification elements such as energy data feedback, competitive mechanisms, and dashboards are employed to incentivize users to actively engage in planning and regulating energy consumption in response to varying indoor environmental conditions and weather fluctuations. Mendez et al. (2021) designed a gamified thermostat interface which depends on the users' personality traits. In this study, fuzzy

logic was employed to engage the users with the thermostat to teach, engage, and motivate end users to become energy aware. The gamified thermostat interface allowed around 15% of energy saving, when compared with the original thermostat system without gamification. Specifically in this project, the gamifying elements of feedback and dashboard were directed towards enhancing the functionality of automated control and system monitoring within thermostats associated with energy consumption. Instead, Das et al. (2019) utilized the gamifying element of reward and dashboard in GUI techniques as a key element to support the visualization of energy-related information for enhanced end-user understanding and obtained an energy use reduction of about 40%. Therefore, it is important to acknowledge that, the visual representation of energy information on dashboard elements directly influences the awareness of users for energy-saving practices.

Similarly, 40% reduction of energy consumption has been achieved with the integration of smart meters, plugs, and sensors within gamification strategy in IoT gamified technique (Ferreira et al., 2022). These strategies allow collection of data in real-time and transfer to backend component of the game application to aggregating energy and sensor data. Smart meters, plugs, and sensors are more focusing on real-time data collection and analysis to put them into functionality of automation system, where the gamifying element of competition in a community engagement and personalised social and challenges can be provided. Paris et al. (2019) applied simulation gamifying element in a social setting of a building automation system, where the sensors server platform is responsible for storing data in the database and changing the settings of the environment to enable the system to run on its own, without supervised control.

As for the HVAC, ICT demonstrates enhanced energy savings, specifically at a rate of 30% (Gangoles et al., 2021). This improvement is

attributed to the incorporation of a social element, which serves to augment participant empathy during gamification interactions, a feeling of belonging can be provided to the end-users during the behaviour and awareness shifting periods. The social element also sustains ongoing participant interest and facilitates the gathering and exchange of information regarding user preferences within the interactive user interface. Compared with the social element, the game element of cooperation can also give users a sense of belonging especially when they are making some changes based on old habits to get out of their comfort zone. Web-based techniques can build a social community for the users to share their experiences and achievements. A card game was developed by Albertarelli et al. (2017) to engage people in using a gamified website platform which offered a wide set of activities aimed at triggering water saving actions. In that work, the portal allowed users to team up to work on the same energy saving task, and implemented an awarding system that combined points and badges to reward water saving behaviours.

In conclusion, the aspects of gamification implementation techniques and operating platform characteristics discussed above underscore the importance of the dynamic tracking of user activities and progress as another crucial aspect of interaction platform. This necessitates the inclusion of dashboard and statistical features. Within the gamified framework, the game design element of competition in IoT and ICT can leverage real-time data to exchange for greater information. In other words, the gamifying element of competition within various users' environments may not only enhances user engagement, but also contributes to the optimisation of energy distribution in building automation systems. Web-based techniques require feedback mechanisms and social interaction to foster community networking, thereby promoting sustained user

engagement. Given the comparison between characteristics of different gamification elements and their energy saving efficiency among different techniques, it is evident that less commonly utilised elements such as simulation and dashboard visualization offer significant energy savings. In contrast, extensively used elements like points and feedback show comparatively lower effectiveness. This suggests that the strategic integration of gamification elements, specifically simulation, dashboard visualization, points, and feedback, is crucial for optimising user engagement and maintaining long-term user interest.

DISCUSSION AND FUTURE RECOMMENDATIONS

In this review study, the examination of common intrinsic systems employed in adaptive façades, characterized by material-oriented designs, reveals the persistence of occupants' overriding behaviours driven by their various environmental preferences, thereby impeding the achievement of energy-saving objectives for façade operations. Conversely, in the case of extrinsic systems equipped with automated control mechanisms, occupants tend to refrain from interacting with the façade, resulting in the loss of adaptability of the adaptive façade to dynamic occupancy environments. Consequently, this scenario hampers the acquisition of pertinent data from occupants necessary for optimizing the operational energy performance of adaptive façades. Hence, there is an imperative to incentivize occupants to actively participate in building energy-saving efforts.

The utilization of gamification strategy as an incentivizing mechanism is under discussion to potentially mitigate the impacts of human factors on energy efficiency goals within adaptive façades. This review suggests that, for the specific objective of promoting user engagement and transforming user energy behaviour, a synergistic approach incorporating Applications (Apps),

Internet of Things (IoT), and Graphical User Interface (GUI) should be considered. Apps provide users with flexible access to gamified systems, independent of geographical constraints, while IoT enables real-time data transformation and facilitates automated intelligent techniques. Simultaneously, GUI serves to visually present energy-related information, promoting user engagement with simplicity. However, the effective implementation of gamification critically relies on the appropriate design of gamification mechanisms.

In the context of the operational convenience offered by intelligent controls, particularly through the utilization of Apps, Human-Machine Interface (HMI), and IoT sensor systems, gamification primarily focuses its efficacy on key building components such as Heating, Ventilation, and Air Conditioning (HVAC) systems, thermostats, and lighting. These components are predominantly supported by an array of sensors, smart meters, and plugs. Nonetheless, there exists a noticeable scarcity in instances where gamification has been applied to building products, warranting comprehensive exploration within this review. Specifically, this review aims to identify precedent cases wherein gamification strategies have been deployed in conjunction with building façades, given that the façade constitutes a pivotal element significantly influencing overall building energy consumption.

Future research endeavours should focus on the consideration of human factors' influences on adaptive façade energy performance. In particular, attention should be directed towards scenarios involving various occupant override behaviours interacting with adaptive façades, along with the assessment methods towards energy consumption and savings. Furthermore, there is a compelling need for more comprehensive research to explore the influence of gamification mechanisms on the energy behaviours of participants within buildings featuring diverse energy cost structures. Such

investigations could elucidate the nuanced impact of gamification within contexts characterized by significant disparities in energy expenses.

CONCLUSIONS

This review study has undertaken an investigation into the impacts of human factors on adaptive façades through an examination of case studies, with a focus on the adaptivity capabilities of energy performance inherent to these façades. The selected studies have underscored two pivotal challenges in current research: occupant-centric responses and occupant-empowered control within adaptive façades. Addressing these challenges holds significant potential for mitigating energy consumption. Importantly, these challenges result in limited data collection from occupants, which could otherwise support the optimization of adaptive façade operations towards energy savings. Moreover, this review has preliminarily explored the concept of gamification concerning occupant engagement and energy efficiency within the realm of adaptive façades. It has been observed that gamified adaptive façades hold the potential to engage occupants in energy-saving activities. This engagement could serve to bridge the communication gap between adaptive façades and occupants while facilitating changes in occupant energy consumption-related behaviour through incentive mechanisms embedded within gamified systems.

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