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Adaptive Offices for People

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State-of-the-Art analysis

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Table of Contents

Document Glossary 5
Executive Summary 6
Purpose of the document 6
Overview of the AdOff Project 6
State-Of-The-Art analysis 7
Smart Buildings and Smart Offices 8
Indoor Environmental Quality and Occupational comfort 9
Lighting conditions 9
Thermal environment 10
Indoor Air Quality 10
Office Layout Design and Workplace Strategy Alignment 11
The workplace as a strategic and dynamic system 11
The evolution of workplace concepts 11
Open-plan offices 12
Neuro-inclusivity and sensory intelligence 12
From density planning to performance metrics 13
Workplace orchestration through reservation platforms 13
Data-analytics and human governance 14
From redesign to continuous adaptation 14
Measurement of Wellbeing and Comfort in Offices 14
Feedback Collection and AI-driven Human-Building Interfaces 16
LLMs as Natural Language Interfaces for Smart Building Management 18
IoT and Sensing Technologies for Smart Offices 19
Control Systems and Building Management Architecture 20
Adaptive Lighting Systems in Office Environments 20
Energy Management and Sustainability in Offices 21
Identified Gaps and Research Opportunities 23
References 25

Document Glossary

Abbreviation	Definition
AdOff	Adaptive Office (project acronym – ITEA 4 project 23048)
AI	Artificial Intelligence
ABW	Activity-Based Working
BIM	Building Information Modelling
BMS	Building Management Systems
CO_2	Carbon Dioxide
HBI	Human-Building Interaction
HCI	Human-Computer Interaction
HVAC	Heating, Ventilation and Air Conditioning
IAQ	Indoor Air Quality
IEQ	Indoor Environment Quality
IoT	Internet of Things
LLM	Large Language Model
NL	Natural Language
NLP	Natural Language Processing
POE	Post-Occupancy Evaluation
SoTA	State-of-the-Art
VOCs	Volatile Organic Compounds

Executive Summary

Purpose of the document

This deliverable (D2.1) provides a comprehensive State-of-the-Art (SoTA) analysis of the technological and scientific domains relevant to the AdOff project. AdOff – Adaptive Office – is an ITEA 4 project (23048) that aims to design an innovative, user-centered office management concept integrating direct user feedback and contextual data into the optimization of office parameters such as layout, lighting, thermal comfort, and energy consumption.

The SoTA establishes a shared knowledge baseline for all consortium partners, documents the maturity of existing solutions, and identifies research and technology gaps that AdOff targets through its modular platform and use cases in Belgium and Portugal.

Overview of the AdOff Project

AdOff (Adaptive Office) is an ITEA 4 project (reference 23048) that develops a user-centered office management concept. The core objective is to design an innovative system that integrates direct user feedback and contextual data into the optimization of office parameters — including spatial layout, lighting, thermal comfort, and energy consumption — supported by a modular, data-driven platform.

AdOff is designed as a modular system enabling consortium partners and future adopters to integrate technology modules according to their needs. This project anchors five use cases: three in Belgium and two in Portugal.

AI-based tools were used to support drafting and language refinement of this document. The authors take full responsibility for the content, which has been critically reviewed and validated.

AdOff

State-Of-The-Art analysis

This State-of-the-Art analysis maps the main scientific and technological domains that form the foundation of the AdOff project at its start. As AdOff aims to develop an adaptive, user-centered office management concept, the project requires an understanding of the current state of research and practice across several interconnected domains, including smart buildings, office layout design, building control systems, sensing technologies, feedback collection, Human-Building Interaction, wellbeing and comfort assessment, and energy management.

The analysis has three main goals. First, it establishes a shared baseline of knowledge across the consortium by identifying the most relevant concepts, technologies, and approaches currently used in the AdOff domains. Second, it highlights the main limitations of existing systems and practices, particularly regarding the integration of direct user feedback, contextual environmental data, and adaptive decision-making in office environments. Third, it helps position AdOff with respect to current scientific and industrial developments by identifying the gaps and opportunities that the project intends to address.

The scientific literature and practice show that important progress has been made in areas such as smart building sensing, IoT-based monitoring, building energy management, adaptive lighting and HVAC control, and workplace analytics. At the same time, most existing approaches remain fragmented. They often focus on isolated subsystems, rely predominantly on indirect sensing, or optimize for building performance without sufficiently accounting for subjective occupant experience, individual variability, or the complexity of shared office environments.

For this reason, the present analysis does not treat the office merely as a technical infrastructure, but as a socio-technical environment in which spatial design, environmental control and user experience are closely intertwined. From this perspective, AdOff is positioned as a project that seeks to bridge the gap between objective building data and lived workplace experience through a modular, data-driven, and human-centered approach.

The following sections therefore review the State-of-the-Art in the core AdOff domains. Together, they provide a conceptual and technical foundation for the research and development of adaptive office solutions.

Smart Buildings and Smart Offices

To reduce global greenhouse gas emissions, the building sector is a key target for intervention, as it is one of the largest contributors (Sonta et al., 2021). Energy consumption in offices is primarily driven by lighting and heating, ventilation, and air conditioning (HVAC) systems. However, the persistent performance gap between predicted energy usage and actual consumption highlights the necessity of incorporating occupant-building interaction models (Yang et al., 2022). As international climate agreements push for net-zero emissions, the pressure to optimize energy use in both new buildings and existing offices is increasing rapidly.

Consequently, both industry and research have pursued technological solutions to mitigate this energy demand. However, reliance on automated Internet of Things (IoT) and rule-based control systems often falls short due to their inability to account for the stochastic nature of occupant behavior and the resulting variability in energy-saving outcomes.

Conventional approaches, such as static schedule-based occupancy sensors, frequently disregard individual thermal and visual comfort preferences, which often leads to occupant dissatisfaction and the deliberate overriding of automated controls. This conflict is exacerbated by the fact that comfort requirements vary significantly across individuals, making one-size-fits-all strategies insufficient for modern workplace dynamics (Auffenberg et al., 2017). Building energy management systems typically rely on static and standardized temperature setpoints that fail to account for individual metabolic rates, clothing insulation, or dynamic occupancy patterns. As a result, this approach leads to poor alignment between energy efficiency objectives and individual thermal comfort needs.

This is further amplified by limitations in traditional comfort models, which often fail to capture individual thermal sensitivity and expectations. As discrepancies between predicted and actual comfort increase, this underscores the limitations of population-based approaches and the need for personalized thermal comfort models (Liu et al., 2019). The sensory capabilities of commercial buildings have evolved significantly in recent years. While traditional binary sensors only detect basic occupancy, modern IoT-based systems enable the collection of fine-grained data, including occupant counts and localized environmental conditions. Moving beyond passive monitoring, recent approaches incorporate feedback loops that use occupant input to continuously adapt system behavior (Yang et al., 2022).

By transitioning toward occupant-centric control, building managers can replace static schedules with real-time optimization algorithms that align HVAC operation with actual human demand (Yang et al., 2022). These strategies aim to improve energy efficiency by dynamically adjusting control setpoints based on occupancy patterns. This approach is also being extended to lighting control, where occupant-centric strategies use occupancy and occupant interactions with lighting systems to balance energy use and visual comfort (Ouf et al., 2020).

Despite these advancements, optimizing shared, open-plan office environments remains challenging. The diversity of occupant environmental preferences introduces challenges for optimizing shared office environments, motivating the need for more adaptive and personalized control strategies (Mofidi & Akbari, 2019).

Recognizing the importance of occupant behavior, recent research increasingly focuses on its role in shaping building energy consumption. Variations in occupant preferences and behavior can significantly influence energy use, highlighting the need to better integrate these factors into building performance models (Torabi & Mahdavinejad, 2021).

State-of-the-Art systems attempt to address this gap by providing real-time feedback through energy dashboards, increasing awareness of consumption patterns. Additionally, behavioral strategies such as gamification are being explored to promote energy-efficient actions and foster user engagement (Fraternali et al., 2019).

Recent work highlights that integrating occupant feedback into building control strategies through user-interactive systems can improve the alignment between energy efficiency and occupant comfort (Liu et al., 2021). However, increasing data granularity raises significant privacy concerns, particularly regarding the collection and use of personal data in smart office environments (Li et al., 2023).

Future research should therefore focus on adaptive and privacy-preserving smart office systems that better balance energy efficiency and occupant comfort by accounting for occupant behavior, individual preferences, and real-time feedback.

Indoor Environmental Quality and Occupational comfort

Indoor Environmental Quality (IEQ) encompasses the environmental conditions within indoor spaces that influence occupants' health, wellbeing, comfort, and productivity. This typically includes the thermal environment, lighting conditions, and indoor air quality (IAQ) and acoustics. In office environments where individuals spend a significant part of their time, IEQ plays a critical role in wellbeing and work performance. Poor IEQ has been associated with reduced productivity and increased health complaints, while improved environmental conditions contribute to enhanced comfort and cognitive performance (Felgueiras et al., 2025; Lamb & Kwok, 2016).

In the context of smart offices and adaptive environments, IEQ is increasingly monitored using sensor networks and integrated into data-driven building management systems. However, achieving optimal IEQ remains challenging due to the variability of individual preferences, dynamic occupancy patterns, and interactions between environmental factors.

Lighting conditions

Lighting conditions are a key component of IEQ and play a critical role in workers' performance, comfort, and wellbeing. Lighting conditions are influenced by several parameters, including illuminance levels, glare, and color temperature. Optimal lighting positively affects worker mood, concentration, and satisfaction (Belany et al., 2024). Research has revealed the broader impact of lighting conditions on occupants, demonstrating that appropriate lighting, especially natural light, enhances worker alertness, comfort, satisfaction, and performance, underscoring its critical role in workplace wellbeing (Fisk, 2017; Wargocki et al., 2000).

Optimized lighting conditions, particularly with high correlated color temperature, have been shown to significantly improve work performance (Mills et al., 2007). Recent findings reinforce that proper workplace lighting is strongly associated with improved visual comfort and overall worker health (Rossi et al., 2024). Beyond productivity, visual comfort has been linked to broader psychological and physiological responses, influencing mood, fatigue, and end-of-day wellbeing (Veitch et al., 2008).

Overall, lighting conditions are not only a matter of meeting minimum lighting standards but also a critical factor in supporting visual comfort, wellbeing, and overall job satisfaction. In the context of smart and adaptive office environments, achieving optimal lighting conditions remains challenging due to variability in individual preferences and the need to balance shared workspace conditions.

Thermal environment

The thermal environment is a fundamental component of IEQ in workplaces, particularly within the context of smart offices. Ensuring adequate thermal conditions is not only a matter of comfort but also of health, wellbeing, and occupant performance. An inappropriate thermal environment has been closely linked to adverse effects.

Thermal comfort is defined as a state of mind that expresses satisfaction with the thermal environment (van Hoof et al., 2010). It is influenced by environmental parameters such as air temperature, relative humidity, air velocity, and radiant temperature, as well as personal factors including clothing insulation and metabolic rate (Zhao et al., 2024).

A substantial body of research has demonstrated the strong relationship between thermal conditions and occupants' wellbeing. Studies have shown that inadequate thermal conditions can lead to measurable reductions in work performance. Furthermore, thermal discomfort is also associated with increased fatigue, negative emotional responses, and decreased motivation (Li et al., 2021; Hancock et al., 2007; Lamb & Kwok, 2016). Conversely, thermal comfort has been linked to improvements in cognitive performance, reduced mental workload, and better overall productivity (Sharma et al., 2025).

Thermal comfort requirements may vary depending on socio-cultural context, individual variables, and adaptive behaviors, highlighting the limitations of standardized models in real-world environments (Sansaniwal et al., 2020). Traditional thermal comfort models alone may be insufficient to fully capture individual variability and dynamic comfort needs, highlighting the importance of integrating objective environmental measurements with user feedback in adaptive office environments.

Overall, thermal comfort is not only a matter of maintaining acceptable temperature ranges but also a critical factor in supporting cognitive performance, wellbeing, and organizational efficiency. In the context of smart and adaptive office environments, achieving optimal thermal conditions remains challenging due to variability in individual preferences and the need to balance comfort with energy efficiency in shared spaces.

Indoor Air Quality

Indoor Air Quality (IAQ) refers to the quality of the air within buildings and its impact on occupants' wellbeing. It is typically assessed through parameters such as carbon dioxide (CO_2) concentration, relative humidity, and concentrations of pollutants including particulate matter (PM_{10} and $PM_{2.5}$), volatile organic compounds (VOCs), and formaldehyde. Among these, CO_2 concentration is widely used as an indicator of ventilation adequacy and occupancy levels, particularly in office environments (Chamseddine et al., 2025). Findings have shown that elevated CO_2 levels are associated with reduced cognitive performance and increased discomfort, while exposure to particulate matter and other pollutants can further impair decision-making and task performance (Künn et al., 2019).

It is known that IAQ has a strong impact on health, comfort, and productivity. Improved air quality has been consistently associated with better cognitive performance, increased productivity, and enhanced overall employee health (Palacios et al., 2021; Vaidhya, 2024; Wyon, 2004). Conversely, poor IAQ has been linked to reduced work performance, increased error rates, and adverse health outcomes, including respiratory symptoms and sick building syndrome (Surawattanasakul et al., 2022; Wyon, 2004).

Overall, IAQ is a critical factor influencing occupants' wellbeing. Its effective management remains a key challenge in smart and adaptive office environments. CO_2 concentration is widely recognized as a key indicator of ventilation adequacy and is commonly used as a primary proxy for assessing IAQ in office environments, particularly due to its strong association with occupancy levels and ventilation performance.

Office Layout Design and Workplace Strategy Alignment

The workplace as a strategic and dynamic system

The office environment is undergoing a profound structural transformation. Traditional planning logic, centered on density metrics such as workstations per square meter, is giving way to performance-driven thinking. Organizations increasingly monitor utilization rates, attendance patterns, sharing ratios and behavioral dynamics rather than static capacity indicators. This shift reflects a broader move toward evaluating workplace performance and employee experience rather than space efficiency alone (Gensler, 2023). The critical question is no longer *"How much space do we need?"* but rather *"How does space continuously align with organizational behavior, performance, and employee experience?"*

This shift reflects a deeper evolution: from the workplace as fixed infrastructure to the workplace as a dynamic ecosystem. The physical office is no longer viewed merely as a cost center, but as a strategic asset within a broader set of initiatives aimed at enhancing employee experience, engagement, wellbeing and organizational resilience.

Yet despite this increased awareness, many organizations struggle to translate insights into effective workplace design. It is important to understand how employees experience and use the workplace, as traditional metrics such as occupancy alone fail to capture this complexity (Leesman, 2025).

The evolution of workplace concepts

Over the past decade, workplace design paradigms have evolved. Early office environments were typically organized around assigned desks and hierarchical spatial layouts. As organizations began prioritizing collaboration and flexibility, new workplace concepts emerged.

Activity-Based Working (ABW) organizes workplaces according to different work activities, allowing employees to choose environments that best support their tasks. This later expanded into neighborhood-based working, which emphasizes team clusters and a sense of belonging.

More recently, environment-based working has emerged, where not only the activity but also environmental factors - such as acoustics, lighting conditions, thermal comfort, visual stimuli and social density - determine the most suitable space. Employees select spaces based on how environments support their sensory needs. This shift highlights that performance depends on both the task and the surrounding environment, though too much variety without clear structure can lead to confusion and reduced effectiveness.

However, diversity alone does not guarantee effectiveness. Increasing spatial variety without clear behavioral logic can lead to confusion. Effective workplace strategies therefore require intentional orchestration: meaningful differentiation combined with clarity, governance and clear usage patterns.

Open-plan offices

The evolution of workplace concepts is closely linked to broader changes in how organizations use office space. The COVID-19 pandemic accelerated hybrid working models and introduced greater flexibility in workplace presence. Industry forecasts suggest that by 2030 up to 30% of office space may be used flexibly (JLL, 2020).

In response, many organizations increasingly adopt open-plan or activity-based layouts to optimize space utilization and reduce real estate costs. At the same time, technological advances have enabled offices to integrate intelligent building systems that automatically regulate parameters such as air quality, lighting, temperature and energy consumption, contributing to the emergence of smart offices.

Despite their economic advantages and intended positive effect on collaboration, open-plan offices remain the subject of extensive debate. Numerous studies associate such layouts with lower satisfaction levels, mainly due to acoustic disturbance, lack of speech privacy and visual distraction (Kim & de Dear, 2013; De Croon et al., 2005).

Post-occupancy evaluations consistently show that most employees experience dissatisfaction with at least one aspect of their workplace environment, particularly related to noise and privacy (Parkinson et al., 2023). While offices often provide adjustable elements such as lighting controls, blinds or thermostats, these are not consistently used, as employees tend to intervene only when discomfort exceeds their tolerance threshold.

Bernstein & Turban (2018) show that open office environments can reduce face-to-face interaction and increase digital communication, suggesting that removing spatial boundaries alone does not necessarily enhance collaboration.

Neuro-inclusivity and sensory intelligence

Alongside these spatial developments, attention to neuro-inclusion is increasing. A substantial proportion of the workforce is neurodivergent, and there is a growing expectation for workplaces that recognise diverse ways of thinking and working (CIPD, 2024).

Research on open-plan offices highlights how environmental conditions can disproportionately affect different users. Noise and lack of privacy are consistently reported as major sources of dissatisfaction, with occupants in open-plan settings experiencing lower satisfaction than those in enclosed offices. Experimental evidence further shows that typical office noise can trigger physiological responses and reduce task persistence, even when users do not explicitly report higher stress levels (Evans & Johnson, 2000). These findings underline how sensory conditions in the workplace can subtly influence behaviour and wellbeing, reinforcing the need to consider diverse sensitivities in office design.

Environmental conditions that are challenging for some users, such as high noise levels or strong sensory stimuli, do not affect all employees in the same way. Designing with a wider range of sensitivities in mind can therefore contribute to more inclusive and broadly supportive workplaces. In practice, workplace design often places strong emphasis on visual qualities such as aesthetics and branding, while other sensory aspects tend to receive less explicit attention. From this perspective, it becomes relevant to more deliberately consider sensory conditions in office design, for example through acoustic zoning, access to low-stimulation spaces, and more controlled visual and auditory environments.

From density planning to performance metrics

As workplace concepts evolve, so do the metrics used to evaluate them. Traditional planning approaches have largely focused on spatial efficiency, using indicators such as density or desk ratios. While these remain relevant from a cost perspective, more recent work increasingly emphasizes how workplaces support different work activities and employee experience (Gensler, 2023).

In practice, this has led organizations to complement traditional metrics with more detailed insights into workplace use, such as patterns of attendance, space utilization over time, meeting behaviors, and employee satisfaction. Rather than focusing solely on how much space is provided, attention shifts toward how effectively that space supports work.

At the same time, the growing availability of workplace data introduces new challenges. Data from booking systems, occupancy sensors, environmental measurements, and user feedback is often fragmented across systems, making it difficult to translate insights into concrete design decisions. As a result, the challenge is not only to collect data, but to meaningfully integrate and interpret it within the design process.

Workplace orchestration through reservation platforms

The rise of desk and meeting room reservation applications illustrates the digital transformation of workplace management. Initially introduced during the pandemic to manage occupancy safely, these tools have evolved into important infrastructure for hybrid work environments.

Globally, organizations increasingly rely on booking platforms to coordinate shared workspaces and meeting rooms. The market for such tools continues to grow rapidly, with many organizations now considering reservation platforms a strategic component of workplace management.

Technology itself is also evolving. Rather than functioning as standalone booking systems, modern platforms increasingly operate as workplace orchestration tools, integrating with collaboration platforms such as Microsoft Teams or Outlook and combining reservation functionality with workplace analytics.

In many organizations, adoption has progressed gradually. Office attendance is often still coordinated through team agreements or fixed presence days. When reservation tools are introduced, this typically happens through phased deployments with a strong emphasis on usability and integration with existing IT systems.

This gradual adoption suggests that reservation functionality alone is unlikely to drive future workplace innovation. Instead, greater value will emerge through integration with wellbeing insights, contextual sensing, and adaptive workplace management.

Data-analytics and human governance

The growing availability of workplace data has accelerated the use of advanced analytics and artificial intelligence in workplace strategy. Predictive modelling and scenario simulation enable organizations to analyze behavioral patterns and anticipate spatial needs (Belfa report, 2025).

Modern workplace ecosystems combine multiple data streams, including booking systems, occupancy sensors, Wi-Fi analytics, environmental measurements, and employee feedback. Through dashboards and heatmaps, organizations can visualize spatial performance and identify opportunities for optimization.

However, technology alone cannot determine how people experience space. While algorithms can detect patterns, they cannot fully predict subjective human perception. Meaningful workplace evolution therefore requires human governance, organizational alignment, and participatory design processes. The workplace of the future is therefore not automated but intelligently steered.

From redesign to continuous adaptation

Hybrid work, evolving team structures, and shifting organizational strategies require workplaces to adapt continuously. Leading organizations are therefore moving away from episodic redesign projects toward iterative spatial optimization.

Key characteristics of this model include continuous monitoring rather than periodic evaluation, pilot-based experimentation, and the use of satisfaction data in relation to specific spatial zones. It also involves the iterative reallocation of neighborhoods and functions, supported by transparent feedback loops with employees.

Within this framework, the office becomes a continuously adaptive system. Workplace evolution should align with business strategy, while business strategy should also respond to the needs and expectations of employees.

Measurement of Wellbeing and Comfort in Offices

The measurement of wellbeing and comfort in office environments relies on multiple approaches, primarily combining Post-Occupancy Evaluation (POE) surveys with objective environmental monitoring, although no universally standardized method currently exists. Evidence shows that environmental factors such as indoor air quality, lighting, and thermal conditions are strongly associated with overall comfort, while personal characteristics also significantly influence comfort perception beyond the build environment alone (Fissore et al., 2023; Sakellaris et al., 2016).

Despite extensive research, a key limitation remains in the lack of a universally accepted definition and measurement framework for office comfort (Haynes, 2008). Studies also indicate that repeated and continuous data collection provides more reliable insights than single-point assessments, and that compliance with environmental standards alone is insufficient to ensure optimal comfort (Roskams & Haynes, 2020).

In practice, workplace assessments are typically conducted by architects or occupational health service providers. They follow international standards, occupational health best practices and healthy building certifications. In Belgium, employers are legally obliged to carry out risk analyses in the areas of safety, health, and psychosocial wellbeing using a dynamic risk management system. These risk analyses must encompass all workplaces, work processes, and employees within the organization, and must be conducted regularly. They are generally linked to the organization's mandatory five-year Global Prevention Plan and must also be carried out in case of significant organizational restructuring. The results of these risk analyses must be documented within the organization's dynamic risk management system and translated into a concrete action plan.

As Belgium's largest external partner in prevention and wellbeing at work, IDEWE provides both general and thematic workplace risk assessments. These assessments are followed by targeted recommendations to manage and mitigate identified risks. IDEWE's current way of working involves a comprehensive approach to workplace safety and wellbeing using the SARIER® method (Systematic Analytical Risk Inventarization, Evaluation, and Registration). This methodology maps the current state of work processes and workplace environments, prioritizes risks requiring immediate action, and provides tailored recommendations for improvement.

In addition, IDEWE also provides thematic risk assessments on key domains such as psychosocial risks and ergonomics. The psychosocial risk assessment (RAPSi) is composed of several validated scales and questionnaires based on the well-established Job Demands-Resources (JD-R) model and complies with the Belgian Welfare Act. The assessment addresses the five legally defined work aspects (work organization, job content, employment conditions, work environment, and work relations), as required by Codex I.3. The JD-R framework allows for investigation of how various psychosocial risk factors influence employee wellbeing. Results are primarily analyzed at group level to support collective prevention measures, while individual participants can also receive personalized feedback and advice aimed at improving their wellbeing. The RAPSi instrument is continuously evaluated and updated following evidence-based practice principles. In 2025, a total of 125,073 employees across 182 organizations participated in the RAPSi survey.

Similar, ergonomic evaluations follow a structured three-step approach that includes mapping the organization's ergonomic policy through participatory consultations, conducting collective ergonomic risk assessments (OptiDesk), and implementing preventive measures. Similar to RAPSi, the OptiDesk tool assesses the impact of ergonomic aspects of the office environment on employees' health and wellbeing. The questionnaire includes items on workstation design, the physical working environment, movement patterns, and physical and visual complaints. After completing the questionnaire, employees immediately receive personalized recommendations to improve their workstation setup and work habits, with referral to a prevention advisor when necessary. In 2025, 8368 employees across 38 organizations completed the OptiDesk survey.

Regarding lighting, IDEWE provides expert advice based on detailed lighting plans (developed using DIALUX 11, DIALUX 12.1 or RELUX), on-site light measurements and the NBN EN 12464 – 2021 standard. In addition, IDEWE supports organizations in obtaining WELL Building certification. Accredited professionals guide organizations through a structured five-step certification trajectory and conduct periodic occupant surveys to support certification maintenance and improve employee experience.

However, despite the breadth of these general and thematic risk assessment tools, several limitations remain. Current workplace assessments are typically conducted periodically and rely largely on either subjective employee feedback (e.g., surveys) or isolated objective measurements (e.g., lighting or environmental assessments). As a result, there is limited integration of multimodal data sources and little capability to monitor workplace conditions continuously or to dynamically link environmental parameters to employees' experiences and wellbeing.

Consequently, organizations currently lack the ability to derive actionable insights from combined datasets capturing environmental conditions, workplace design parameters, and employee feedback over time. This limits the potential to proactively optimize office environments based on real usage patterns and individual needs.

Recent advances in sensing technologies, data integration, and artificial intelligence offer new opportunities to address these limitations. By combining environmental monitoring, contextual data, and direct user feedback, AI-driven systems can generate deeper insights into how office conditions influence wellbeing, comfort, and productivity. The AdOff project aims to explore and operationalize these opportunities by developing an adaptive office management concept in which integrated data streams and AI-based analytics support evidence-based and user-centered optimization of workplace environments. AdOff seeks to generate actionable insights that enable organizations to design and manage healthier, more comfortable, and more energy-efficient workplaces.

Feedback Collection and AI-driven Human-Building Interfaces

Traditional approaches to evaluating IEQ in offices often rely on surveys conducted at the scale of an entire workforce. However, such approaches may fail to capture the situated and personal nature of environmental experiences, which can vary significantly (Jayathissa et al., 2020). The EnviroMapper Toolkit (Cazacu et al., 2025) captures environmental comfort feedback by mapping occupants' experiences to specific locations and moments within the workplace. Deployments in open-plan offices show that spatially anchored feedback can reveal context-dependent comfort experiences that may not be captured by traditional surveys, highlighting the importance of fine-grained and situated occupant feedback.

Human-Building Interaction (HBI) is a field that refers to interaction between building occupants and the built environment. The concept has been introduced as an emerging research domain that frames Human-Computer Interaction (HCI) research within built environments and positions it at the interface between HCI, architecture, and urban design (Alavi et al., 2019). Within this domain, researchers investigate how digital technologies embedded in buildings can support more effective communication between occupants and the built environment.

Research increasingly explores how artificial intelligence can support the analysis of building and occupant data. AI techniques are increasingly used in smart building systems to process large volumes of sensor data to support proactive management of indoor environmental quality, comfort, and energy performance (Amangeldy et al., 2025). Recent research further investigates the integration of Large Language Models (LLMs) as interactive interfaces between occupants and building systems. For example, LLM-based AI agents have been proposed for building energy management systems that analyse contextual building data and interact with users through natural language in order to provide insights and manage connected devices (He & Jazizadeh, 2025).

However, several challenges regarding the use of AI remain, such as the fragmentation of building data across heterogeneous systems, concerns related to the handling of sensitive personal data, and the need for more transparent and explainable AI approaches (Amangeldy et al., 2025). A literature review of HBI research analyzed more than 900 publications and identified several key research directions in the field, including automatic climate control, lighting control, window control, and AI-driven building operation (Kim et al., 2023). The review discusses challenges related to sensing, prediction, and control processes of HBI systems. These include limitations in capturing local environmental conditions, insufficient data for accurate prediction models, and difficulties in integrating individual comfort preferences within shared building control strategies.

Recent work also investigates how feedback collection mechanisms should be designed. Experience sampling approaches allow occupants to provide in-the-moment reflections about their workplace environment, capturing contextual aspects of wellbeing that are difficult to obtain through environmental sensing alone. A recently proposed system, Click-IO, demonstrates how tangible and mobile interaction devices can enable real-time feedback while addressing challenges related to privacy and interaction burden (Brombacher et al., 2024). A field study deploying two lighting control interfaces in a real office environment, a smartphone application for desk lighting and tablet interfaces for meeting rooms, investigated how occupants experience lighting control in practice. The results informed design considerations related to interface characteristics, shared control, and hybrid interaction with automated lighting systems (Van De Werff et al., 2019).

These studies highlight the growing importance of designing effective Human-Building Interfaces to capture situated occupant feedback. While advances in sensing, interaction design, and AI offer new opportunities for human-building communication, integrating these elements into coherent and scalable feedback frameworks remains an open research challenge.

LLMs as Natural Language Interfaces for Smart Building Management

LLMs and chatbots have increasingly established themselves as a Natural Language (NL) based interface between users and building systems, enabling more direct interaction with complex and heterogeneous data. It is shown that these approaches facilitate communication between occupants, operators, and digital platforms, reducing the complexity of traditional interfaces and promoting greater accessibility to information (Arslan & Munawar, 2026). In this context, LLMs can function as intermediaries capable of interpreting requests, structuring knowledge, and supporting monitoring and decision-making processes in smart buildings, including applications in energy and operational management.

Regarding the collection and analysis of occupant feedback, LLMs have been used to analyse unstructured textual data related to IEQ (Sadick & Chinazzo, 2025). The presented results showed that fine-tuned models can automatically classify comments across multiple dimensions (e.g., thermal comfort, acoustics, and air quality), enabling the transformation of qualitative feedback into structured information to support operations. In parallel, it is shown that chatbots based on Natural Language Processing (NLP) can support information retrieval in facility management, especially when integrated with Building Information Modelling (BIM) and ontologies (Chen & Tsai, 2021).

In the domain of BIM and conversational interfaces, the system DAVE is a relevant example of applying LLMs as a Human-Building Interface (Fernandes, et al., 2024). This assistant enables interaction with BIM models through Natural Language (supporting both voice and text commands) and demonstrates the ability to interpret instructions and execute tasks in real time. It is shown that DAVE can correctly respond to a wide range of requests, facilitating the querying and manipulation of model information while reducing the need for advanced technical knowledge. Additionally, LLMs have been integrated with contextual information, such as user location and activity, to support the development of context-aware chatbots that adapt responses to the user's current context (Polo-Rodríguez, et al., 2025).

Several applications of LLMs in building energy systems have been identified, including data integration, decision support, and natural language-based energy control (Arslan & Munawar, 2026). However, recent work indicates that, despite strong performance in technical tasks, LLMs face limitations in considering sociotechnical, economic, and contextual factors, particularly in more complex decision-making scenarios (Shu, et al., 2025).

Overall, the reviewed works suggest that LLMs and chatbots, including systems such as DAVE, have significant potential as natural language-based interfaces for smart buildings, while also highlighting limitations related to reliability and the handling of complex contextual and decision-making requirements.

IoT and Sensing Technologies for Smart Offices

This section examines the integration of IoT-enabled sensing solutions within smart office environments to optimize energy efficiency, occupant comfort, and operational productivity (Alsafery et al., 2023). These systems typically rely on hierarchical architectures, ranging from edge-sensing layers that capture environmental variables to cloud-based processing units that support highly computational-demanding models (Piras et al., 2025).

IoT technology plays a significant role in smart buildings, commonly acting as the foundational technology that interconnects sensors, devices, and cloud platforms to enable real-time monitoring, remote control, and optimization of energy use, occupant comfort, and operational efficiency (Alsafery et al., 2023). By deploying IoT-based solutions, buildings can be retrofitted to improve energy efficiency and energy management (Vadruccio et al., 2023). Such interventions enable the integration of IoT technologies into existing buildings and support their transformation into smart building systems (Ademowo, 2025).

Despite the potential of IoT-based solutions in enhancing energy efficiency, occupant comfort, and productivity in smart offices (Alsafery et al., 2023), their adoption also raises important privacy and security concerns. The data collected through sensors can reveal detailed information about occupants' behavior and activities, which may be misused without appropriate safeguards. In addition, the increasing number of connected devices introduces risks related to system vulnerabilities, data breaches, and other malicious activities (Alsafery et al., 2023). For instance, occupancy detection systems, while supporting space utilization analysis, may enable the tracking or inference of occupant movements, raising questions around privacy, consent, and data ownership. These concerns can be particularly relevant in retrofitted buildings, where existing infrastructure may not have been designed with such data collection in mind.

The rapid growth of IoT devices and the increasing scale of interconnected systems introduce new security challenges and privacy risks, highlighting the need for more advanced and adaptive security approaches (Goli & Kim, 2021). IoT systems do not only inherit existing IT security risks but can also amplify them through the use of shared technology platforms and increasingly interconnected and heterogeneous device ecosystems (Brennecke et al., 2025). As a result, they are exposed to a wide range of cyber threats, with prior work categorizing attack types such as distributed denial-of-service attacks, ransomware, and other forms of intrusion targeting IoT infrastructures (Sharma et al., 2022). These vulnerabilities highlight the need for robust security measures, as IoT devices remain susceptible to cyberattacks, particularly due to inadequate patching and security updates (Jaafar et al., 2024).

The increasing use of heterogeneous IoT devices in workplace environments introduces additional challenges in managing and interpreting data. Sensor-based datasets are often incomplete due to failures or inconsistencies in data collection. This can significantly affect downstream analysis, making data imputation a critical step in ensuring reliable insights (Decorte et al., 2024). Existing work shows that methods leveraging spatial and temporal correlations between sensors can effectively reconstruct missing values in such datasets. Data fusion is increasingly used to integrate multiple data streams in building-related applications. By combining different sources of information into more informative feature sets, such approaches can improve the accuracy and robustness of building performance models

(Choi, 2025). Integrating and managing real-time data from multiple sources remains a key challenge in smart building systems, particularly in the context of digital twin implementations for facility management (Ghansah, 2024).

Within Human-Building Interaction research, user modelling increasingly relies on sensing technologies, such as wearables, to capture more detailed information about occupants, enabling more adaptive and responsive building control strategies (Becerik-Gerber et al., 2022). Research has shown that workspace environments can be dynamically adjusted based on physiological feedback, enabling adaptive control strategies that influence occupant focus and stress levels (Zhao et al., 2021).

Control Systems and Building Management Architecture

The current State-of-the-Art in control systems for smart offices and buildings is evolving from traditional Building Management Systems (BMS) toward more distributed, software-defined, and data-driven control architectures. Conventional systems rely on hierarchical, rule-based control strategies with limited flexibility and interoperability. Recent advances introduce model-based control approaches, including Model Predictive Control and reinforcement learning, enabling predictive optimization of HVAC, lighting, and energy systems based on occupancy, environmental conditions, and energy demand. In parallel, event-driven architectures and lightweight messaging protocols known from the IT world are increasingly adopted, often combined with edge computing to support low-latency, real-time control closer to physical assets.

Despite these technological advancements, the current generation of control systems remains relatively immature in terms of adaptability, interoperability, and especially user interaction. Most systems still operate with limited integration of real-time occupant feedback and rely predominantly on indirect sensing rather than explicit human input. As a result, control strategies often fail to capture the subjective and dynamic nature of occupant comfort and behavior, particularly in shared office environments.

Furthermore, fragmentation across vendors and subsystems continues to hinder the development of unified, scalable control frameworks. This highlights a key gap addressed by AdOff: the need for human-centric, adaptive control systems that integrate direct user feedback, contextual data, and modular control logic into a coherent architecture. By bridging the gap between advanced control technologies and meaningful Human-Building Interaction, AdOff positions itself beyond the current State-of-the-Art, enabling more responsive, transparent, and user-aware office environments.

Adaptive Lighting Systems in Office Environments

Artificial lighting affects health and wellbeing through its intensity, spectral, and angular distribution. Current lighting systems are designed with a focus on aesthetics, energy efficiency, sustainability, glare control and color tunability. They can operate either statically, through a single switch with or without dimming, or dynamically based on presence detection, predefined lighting profiles, or control by a building manager.

However, the potential on occupants' health and wellbeing is typically not considered, as contextualized user feedback is rarely collected. Current lighting systems already allow an office occupant to individually control his/her preferences via a personal device. These solutions, however, have a broad resolution and do not consider the influence of individual actions on the group's lighting comfort, let alone multiple coexisting situations in the same office.

Optimal mesh solutions that adapt to the global scene maximizing the comfort of all employees are lacking. Additionally, existing user controls are often complex to use, finding the optimal individual setting and not uniform over the multiple spaces where occupants come, especially in shared offices.

Current smart lighting systems adjust their intensity and/or spectral emission in function of occupancy and daylight presence by means of passive infrared sensors and ultrasonic detectors. Measurements from different sensors in the same area are captured through a wireless mesh network. Optimization variables in such scenarios are energy consumption and user comfort. The last as defined by international standards for lighting in working spaces such as EN 12464-1.

In a research setting, the presence of occupants has been used to dim the light of multiple luminaires, and in some cases also to adapt their emission spectrum. But as stated before, the illumination control that is offered by a system consisting of multiple luminaires with a fixed radiation pattern is quite limited.

An attempt to operate a lighting system based on an occupant centered controller with reinforcement learning has been demonstrated. However, the control was limited to an on-off switch, hence, ignoring the intensity levels as well as the angular light distribution. Furthermore, there was only one occupant per space.

So far, the current smart lighting systems, can be operated via a customized API and integrated along with sensing edge devices in a BMS to control the intensity and the angular distribution. However, it still lacks a mechanism to retrieve, interpret, or use feedback from employees who occupy a shared space, such as an open office.

Energy Management and Sustainability in Offices

Building energy management systems are a key topic for improving the efficiency of buildings, enabling the achievement of sustainable net-zero energy buildings (Ahmed et al., 2022) and the active participation of buildings in smart grids (Toderean et al., 2025). While numerous optimization and management models have been proposed in the literature, their application is often more effective when considered during the design phase, as post-construction interventions tend to be more complex and resource-intensive (Manmatharasan et al., 2025). Additionally, the consideration of users in energy management models remains limited, as many approaches primarily focus on energy optimization, with less attention given to user needs, preferences, and comfort.

The acceptance of building energy management systems is highly dependent on building users. Users will accept the system if their comfort is not compromised and will reject it if the system negatively affects their comfort or normal activities. When dealing with smart buildings, this topic has been studied in the past but is not always prioritized in energy management systems (Moeller, 2024). In larger buildings with many users, the diversity of needs, preferences, and comfort requirements introduces additional complexity. This is sometimes addressed through individual or user-centred control approaches, particularly in lighting systems, where accommodating individual preferences has been shown to be important but challenging to implement (Hammes et al., 2024). However, this approach is not suitable for shared spaces with single resources, such as HVAC units in an open-space office. Additionally, certain user groups may have difficulty providing reliable feedback on their comfort levels, introducing further complexity to modelling approaches (Song & Calautit, 2024).

Energy management systems in offices frequently include monitoring, control, and optimization features that collect data in real time from sensors, meters, and building automation systems. These technologies allow the analysis of patterns in energy usage and enable automatic or semi-automatic decision-making to improve energy efficiency while maintaining indoor comfort (Billanes et al., 2025). Through the integration of data-driven technologies and advanced analytics, buildings can dynamically adjust operational parameters based on occupancy patterns, environmental conditions, and energy demand, thereby improving building performance and sustainability outcomes.

HVAC systems, responsible for maintaining indoor thermal comfort, account for a significant proportion of energy consumption in office buildings. These systems are therefore a primary target for optimization efforts since they represent a considerable share of total commercial building energy use. Recent studies have explored advanced control strategies such as model predictive control, reinforcement learning, and hybrid artificial intelligence techniques to improve HVAC performance (Gunasinghalge et al., 2025; Yang et al., 2025). These approaches can predict thermal loads, weather conditions, and occupancy patterns to optimize temperature setpoints and airflow rates, achieving higher energy efficiency while maintaining occupant comfort. Beyond energy savings, HVAC operation plays a central role in shaping indoor thermal comfort, which is an important factor for occupant wellbeing.

Lighting systems are another important opportunity for energy reduction in office environments. Smart lighting solutions integrate sensors, occupancy detection and control algorithms to adjust illumination levels based on usage conditions (Obioma et al., 2025). Such systems can significantly reduce energy consumption while maintaining appropriate lighting and visual comfort. The integration of Internet of Things (IoT) technology enhances these solutions by enabling communication between devices, building systems, and users.

Another important factor is the interaction between modern energy management systems and smart grids. Smart buildings can actively participate in demand response programs by adjusting their energy consumption in response to electricity price signals or grid requirements. Through energy storage technologies and predictive analytics, buildings can store excess renewable energy, shift loads, and optimize energy use across multiple systems.

Despite these technological advances, several challenges remain in the implementation of energy management systems in office buildings. One of the main challenges is the integration of different building subsystems, such as lighting, HVAC, and renewable energy generation, into a unified optimization framework. Many existing approaches still focus on individual subsystems rather than holistic building-level optimization, which limits their overall impact on energy efficiency (Gunasinghalge et al., 2025). Furthermore, implementation barriers, including economic and technical challenges, continue to hinder the widespread adoption of advanced energy management solutions.

Consequently, current research trends highlight the development of integrated and user-centric energy management systems that combine energy efficiency with occupant comfort and behavior modelling. These approaches aim to bridge the gap between technological efficiency and user satisfaction, enabling the deployment of intelligent building systems that are both sustainable and acceptable to building occupants. The integration of energy management, smart lighting, HVAC optimization, and smart grid participation will therefore play a key role in the development of sustainable and energy-efficient office buildings as building infrastructures become increasingly smart and connected.

Identified Gaps and Research Opportunities

The State-of-the-Art analysis shows that substantial progress has been made in the domains relevant to AdOff, including workplace design, occupant wellbeing assessment, sensing technologies, Human-Building Interaction, adaptive control, lighting systems, and building energy management. At the same time, the review also reveals that current approaches remain fragmented and only partially capable of supporting truly adaptive, user-centered office environments.

The first major gap concerns the limited integration of heterogeneous data sources. Existing approaches often rely on separate streams of information, such as environmental sensing, occupancy monitoring, booking data, or employee surveys, without combining them into a coherent and operational decision-making framework. As a result, organizations may collect large amounts of data, while still lacking the ability to translate these data into actionable spatial or operational interventions.

A second gap relates to the limited role of direct occupant feedback in current smart office systems. Many solutions continue to rely primarily on indirect sensing or standardized comfort models, while the situated, subjective, and dynamic nature of employee experience is insufficiently captured. This is especially problematic in shared office environments, where needs and preferences vary across individuals, activities, and moments in time.

A third gap is the weak connection between workplace experience and building operation. Spatial layout, indoor environmental conditions, user perception, and energy performance are often addressed as separate problem domains rather than as interdependent dimensions of one office ecosystem. This separation limits the development of adaptive solutions that can balance comfort, wellbeing, workplace functionality, and sustainability.

A fourth gap concerns the maturity of existing control and adaptation mechanisms. Although advances in IoT, artificial intelligence, predictive control, and adaptive lighting have created new possibilities, many current systems remain rule-based, reactive, or insufficiently transparent. Their ability to support fine-grained adaptation in shared office environments remains limited, particularly when multiple occupants with different preferences need to be accommodated simultaneously.

Finally, the review confirms that interoperability, scalability, privacy, and explainability remain persistent challenges across the field. Smart office solutions are often hindered by fragmented technical infrastructures, vendor-specific ecosystems, and concerns related to the collection and use of occupant-related data. These issues continue to constrain large-scale and long-term adoption.

Against this background, AdOff is positioned as a project that responds to several persistent limitations in the current State-of-the-Art. AdOff therefore aims to build a more integrated and human-centered approach to office management, combining contextual data, user feedback, adaptive control, and energy-aware optimization. In doing so, the project responds to identified gaps in current research and practice and contributes to the development of healthier, more comfortable, and more efficient office environments.

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