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Enabling Sufficiency Through Smart Locks: Transforming Office Occupancy and Building Management for Energy Savings

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Abstract: In the aftermath of the global pandemic, the widespread embrace of flexible working models has led to suboptimal occupancy levels in office buildings. Despite this shift, traditional space management practices persist, contributing to increased energy consumption per person. This study investigates how integrating smart lock systems can enhance space utilization within flexible working environments, ultimately reducing energy use. A case study of an office building in Milan, Italy, is used to evaluate the proposed approach. The methodology includes a comprehensive assessment of building design and functionality, coupled with impact analyses using Building Energy Modeling and Life Cycle Assessment. The results indicate that innovative occupancy management strategies can achieve energy savings of from 9% up to 14% compared to baseline operational energy use, leading to a reduction in CO_2 emissions of 7.5 to 17.6 $kgCO_2eq/m^2$ depending on occupancy scenarios. The life cycle assessment reveals that, while smart locks introduce an initial embodied carbon footprint of approximately 2 tons of CO_2, that is recovered through the savings obtained after a few months of installation. The findings demonstrate that this methodology is effective in buildings that allow both functional and temporal flexibility, enabling partial shutdowns and the redirection of certain services when not in use, ultimately improving energy efficiency through lean interventions.

Keywords: occupancy-based control strategies; sustainable occupancy management energy optimization; wise lock systems; LCA; payback period; smart building design

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1. Introduction

Global energy demand is increasing, raising environmental concerns [1]. Buildings are a significant contributor, responsible for 37% of global CO_2 emissions [2], due to both operational and embodied carbon. However, interventions for energy savings in buildings do not often consider the added embodied carbon. Poor attention to the embodied component when designing building energy improvements results in an increasing importance of the share of embodied carbon in the total emissions of buildings [3]. Consequently, the development of low-impacting strategies to reduce buildings' energy needs is today a major concern [4]. Occupant behaviour, building envelope, and building energy systems are the three main elements that contribute to a building's overall energy performance: optimizing these elements can help achieve energy efficiency while maintaining low embodied carbon. Despite advancements in building envelope efficiency, evidence underscores the substantial energy end-use attributed to small power and ICT equipment, as well as lighting [5]. This multifaceted scenario necessitates a comprehensive understanding and strategic interventions to reach Europe's sustainability goals.

At the same time, the adoption of work-from-home (WFH) has grown steadily over the past decade, with the COVID-19 pandemic accelerating this trend. In the U.S., only 20% of workers had remote arrangements pre-pandemic but, by October 2020, 71% worked remotely most of the time, with over half preferring to continue [6]. In the EU, remote work rose from 5.5% in 2019 to 12.3% in 2020, reaching 13.5% in 2021.

This shift, alongside climate concerns, highlights the energy waste of underutilized office spaces. Researchers have found that the carbon footprint of an office staff is as much as 5263.16 kg CO_2eq per year [7] and that, if office workers telecommuted at least once a week, global oil consumption could drop by 1%, reducing CO_2 emissions by 24 million tons annually [5]. Cost savings and employee preferences are pushing organizations toward hybrid models and the rethinking of office space [8]. Some are reducing floor area per person and adopting flexible seating based on location and schedule [9]. This approach improves spatial efficiency, job satisfaction, and energy performance [10].

In this context, the integration of smart building technologies offers a promising solution for efficient space utilization and energy management of office buildings [11]. Smart systems, including IoT sensors, advanced building management systems, and intelligent access control mechanisms, enable real-time monitoring of occupancy, environmental conditions, and energy use. Additionally, optimizing occupancy patterns can further improve operational efficiency, as research shows significant discrepancies between expected and actual building usage [12,13].

Given the urgency of mitigating climate change and improving workplace efficiency, this study explores innovative methodologies leveraging smart access systems to reduce energy waste. By integrating occupant-centric control strategies and flexible workspaces, buildings can significantly cut energy consumption while adapting to evolving work models in the post-pandemic era [14,15].

In this framework, we propose a workflow for defining occupancy-based space usage layouts utilizing automated access control devices. This workflow is tested on a case study, assessing its effectiveness in reducing operational carbon. Additionally, we evaluate the increase in embodied carbon due to the integration of smart locks and compare it to the reduction achieved during the operational phase.

2. State of the Art

2.1. Types of Intervention for the Reduction of Energy Use in Buildings

Different strategies can be used to reduce a buildings' energy needs: Goh [16] categorizes retrofit technologies into "active strategies", such as advanced technologies for energy supply and efficiency, and "passive strategies", such as building design. This classification mainly addresses interventions related to the reduction in energy losses due to technical inefficiencies, while other classifications also include strategies dedicated to managing the energy demand. Madushika et al. [17] classify energy retrofitting strategies into two main categories: those focused on energy conservation and those focused on energy efficiency improvements. The first group includes strategies such as the generation of renewable energy, the reduction of building energy use, and profile switching of energy use. The second group also includes retrofit technologies that focus on managing energy demand or human factors, which typically have a smaller initial impact because they involve minor modifications to the building, resulting in lower amounts of embodied energy. Eventually, interventions aimed at reducing energy needs can be classified based on the extent of modification to the building itself [14].

Typically, standard retrofit technologies require significant intervention in the building. Examples include applying an external insulation layer or upgrading the HVAC system. However, the material and thickness of the insulation layer should be carefully evaluated to avoid the insulation impact outweighing its benefits [18]. On the other hand, substitution of an HVAC system could increase the embodied carbon of an office building in the range of 15–36% [19]. In addition, some strategies are developed without consideration for the number of occupants or the functional classification of spaces, often leading to discomfort among users [20]. Figure 1 resumes the retrofit strategies in relation to the weight of intervention.

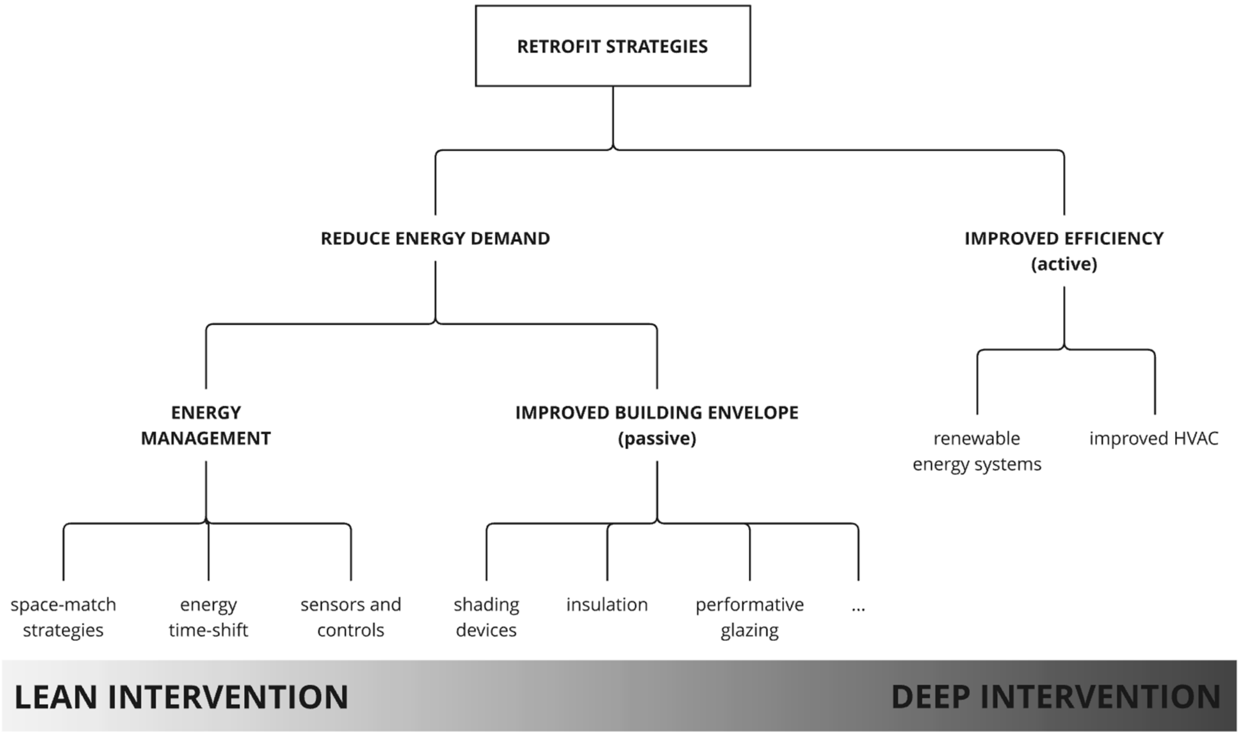


Figure 1. Classification of retrofit strategies in relation to weight of intervention. Author's elaboration on the base of [13–20].

By implementing or co-implementing strategies aimed at managing energy demand and the human factors influencing it, it is possible to mitigate the carbon footprint generated by retrofit interventions. In this view, energy sufficiency measures and principles are crucial in the building sector, encompassing strategies that minimize demands for energy and materials, while enhancing human well-being and impacting energy and carbon emission boundaries [21]. Lastly, space-match strategies focus on optimizing space utilization for energy need reduction and enhanced thermal comfort [10].

2.2. Impact of Occupancy Patterns on Energy Performance

The role of occupants in the energy performance gap of buildings has attracted attention. While some studies suggest that occupants are the main cause of the energy performance gap, evidence for this claim is not sufficiently substantiated [22]. Nevertheless, comprehending occupant behaviour and motivations can yield significant advantages for both the energy efficiency of buildings and the comfort of occupants [23,24].

One clear result in assessing real occupancy is the reduction in energy for heating and cooling: reducing heating during unoccupied hours can lead to significant energy savings in residential buildings, with potential savings of 6–9% for the whole building and 3–13% for individual apartments [25]. Occupancy rates also have a significant correlation with electricity consumption for lights and appliances in both commercial and residential buildings. Considering whether occupants are present or absent during building operations can result in energy savings ranging from 10% to 40% [26]. Additionally, occupancy has a significant impact on the energy efficiency of HVAC systems, with occupancy transitions, variations, and heterogeneity all influencing energy consumption [27]. By accurately representing occupancy schedules and considering the impact of occupancy time on energy upgrade selection, it is possible to make informed decisions for energy upgrade selection based on occupancy patterns, leading to reduced carbon emissions and energy consumption costs [28].

A second area of intervention is related to occupants' behaviour. In a low automated building, occupants have the freedom to interact with the environment at different levels: turning lights on and off, adding or removing appliances, opening doors and windows, or simply rearranging and clustering within the space. Occupant behaviour models show that occupant compromise and clustering effect increases with higher occupancy, leading to a performance gap between actual and expected energy consumption [29,30]

In this context, managing occupancy levels emerges as a significant issue. Salimi et al. [31] analysed different dimensions of building energy efficiency research related to occupant behaviour and categorized them into three main categories: occupancy-based system controls, modelling and monitoring techniques for accurate occupancy data, and automated strategies to encourage energy-efficient behaviour among occupants. The following sub-chapter will examine how these strategies can be implemented through smart building technologies.

2.3. Smart Building Technologies for Occupancy Management and Energy Efficiency in Buildings

Smart building technologies, including IoT sensors, advanced building management systems, and intelligent control mechanisms, are crucial for optimizing building operations and improving energy efficiency. These technologies provide real-time data on occupancy, environmental conditions, and energy usage, enabling dynamic control and automation to enhance overall performance. Wireless sensor networks, for example, are widely recognized by HVAC experts as effective tools for promoting energy efficiency in buildings [32].

Smart occupancy sensors enable buildings to adjust lighting, heating, ventilation, and air conditioning (HVAC) systems based on actual occupancy [33], leading to potential significant energy savings. However, the savings related to the installation of control systems can be uncertain due to the efficacy of the sensor network itself and correct/incorrect user interaction with the automated controls. Bäcklund et al. [34] review 120 research articles that report simulated or measured energy savings resulting from the introduction of automated building control systems.: the savings range from a minimum of 5%, for all types of control, to a maximum of 60%, scored by controls on lighting systems.

In reference [35], different methodologies have been developed to estimate [15] the increase in energy needs due to variations in occupancy schedules through the aggregation and manipulation of sensor data. Sood et al. [36] provide schedules for each typology of residential dwelling through the analysis of the UK TUS dataset. In another notable study, Mitra [31] leveraged data spanning 12 years from the American Time Use Survey (ATUS) to craft typical occupancy schedules across a spectrum of household types and occupant age ranges. Although, in many instances, these schedules align closely with the ASHRAE 90.1 standard [37], disparities of up to 41% have been identified.

By analyzing the data collected from smart occupancy sensors, building managers can gain insights into individual occupant behaviour and tailor energy efficiency strategies to meet their specific needs. Often, the installation of sensor networks for occupancy schedule detection is too expensive: Rafsanjani et al. [38] suggest a non-intrusive occupant load monitoring approach, which combines occupancy-sensing data from existing Wi-Fi infrastructures with changes in overall building energy usage, enabling the disaggregation of building-wide data to individual occupants without intrusive measures. Others [39] leverage the power of neural networks to predict occupancy schedules from indirect measurements, such as ambient temperature, light, and carbon dioxide. Evaluating the ease of installation and integration of occupancy sensor systems is crucial. This involves assessing how easily the sensors can be brought into operation and can continuously operate over time.

Building energy codes tend to reward buildings that perform well under steady and near-capacity occupancy conditions, but strategies like demand-controlled ventilation and occupancy-controlled lighting can optimize energy performance in partial and fluctuating occupancy scenarios [40]. Partial occupancy scenarios, such as teleworking, can be managed through technologies that adapt building systems to reduce energy consumption during low occupancy periods [41]. Varying the space allocation strategy in an office building can lead to over 3.5–15.1% change in annual/monthly energy consumption and over 15% change in average thermal comfort. This highlights the need for joint optimization of HVAC operation and space allocation [42,43].

Under this perspective, smart systems can be designed to implement a different type of energy optimization strategy: rather than solely focusing on modelling building systems or occupancy schedules to match real occupant behaviour, a more proactive strategy involves influencing users to occupy specific zones of the building at designated times. Smart access systems are traditionally developed to ensure security for access to buildings, but they can serve as valuable technologies to help office building managers implement space optimization strategies [44,45]. Different types of access control exist, and their implementation is strictly related to the typology of building, level of security and easiness of access required. Smart access control systems leverage advanced technologies, such as biometric authentication and mobile-based solutions, to enhance security while maintaining ease of access. These systems can be broadly categorized into biometric and non-biometric methods, each offering distinct advantages and challenges.

Biometric authentication methods provide a high level of security by verifying unique biological traits [46]. These systems have become increasingly sophisticated, integrating different types of identifiers, such as facial recognition and thermal imaging in the case of multi-biometric systems, while using visible light and infrared detection in the case of facial recognition systems. Despite their effectiveness, biometric systems may raise privacy concerns and demand significant infrastructure investment. For this reason, they are better suited for high-risk, high-tech, and advanced applications rather than for access control in buildings.

Non-biometric methods offer alternative solutions that balance security and ease of implementation. These systems are often integrated with mobile technologies or traditional physical access mechanisms. By allowing personal mobile devices to function as access credentials, mobile integrated access systems enforce security policies through app-based authentication checks. This method provides flexibility and reduces reliance on physical keycards [47]. Though not extensively covered in recent literature, traditional keycard access remains a widely used method. These systems rely on physical cards that users swipe or tap to gain entry. Non-biometric systems provide practical and scalable solutions but may lack the robustness of biometric authentication.

2.4. Embodied Carbon in Devices and Systems for Operational Energy Optimization

The urgency of mitigating the environmental burdens on buildings and, in particular, carbon emissions due to operational energy requires a deep understanding of the implications of possible technologies over their life cycle. Occupant behaviour is a major driver of emissions and building automation plays a key role in mitigating and distributing occupancy-driven energy demand. However, a full accounting of the environmental impacts and savings is still lacking. Scientific studies which systematically investigate embodied carbon, energy and related environmental impacts of building automation and, in particular, smart locking systems, are very few and a large gap needs to be covered in order to provide important knowledge about the advantages of those systems for achieving carbon neutrality in the built environment.

Vakalis et al. [48] reviewed the interdisciplinary literature on life cycle assessment (LCA) of Internet-of-Things (IoT) in buildings, encompassing emissions from pre-deployment to end-of-life, as well as savings from reduced building operational emissions, in order to evaluate the environmental impact of the devices used. However, since a systematic review was beyond the scope of the paper, the authors acknowledge potential gaps in their arguments and recommend future systematic approaches.

Rangaswamy et al. [49] conducted an LCA of retrofit room automation (RRA) module to investigate potential savings from building automation systems (BAS) when compared to non-automated systems. They found that the impact from the BAS module was greater than the one from the non-automated module, mainly due to the high energy required for the manufacturing of the smart module. Additionally, they found that the embodied energy in BAS cannot be paid back in 10 years (assumed lifespan) by the installation and use of RRA modules. Therefore, they concluded that the RRA module with BAS was problematic, even though it remains one of the most promising options for sustainable and smart buildings in future.

Andersson and Grenthe [50] evaluated a cradle-to-gate LCA of three different types of locks that vary from a traditional mechanical lock to a future concept cylinder accessible through a smartphone. The study aimed to determine and compare the direct environmental impact of the locks and to quantify the potential benefits each lock could generate for downstream customers. It was found that digital locks have a significantly larger direct environmental burden at both product and system levels compared to conventional locks. However, in two out of the three cases under investigation, the reduced operational emissions were large enough to exceed the direct environmental burden of the digital lock system. Based on these results, it was concluded that digital products have the potential to reduce emissions among end users and are not necessarily less sustainable compared to mechanical locks, despite containing electronics. Finally, an important finding was that digital systems may create behavioral changes in the end users, which can result largely in avoided emissions.

3. Materials and Methods

3.1. Framework

The current research aims to adapt energy-building schedules into flexible and hybrid working models using smart system technology. The objective is to assess the environmental benefit of the implementation of space usage strategies through smart access devices to manage occupants' flow within the building, while information related to the cost reduction of costs can be found in [51]. The building energy and cost savings due to the use of space match strategies are assessed through Building Energy Modelling (BEM) and compared to the embedded energy and carbon in the production and installation of smart lock systems (estimated through LCA). The proposed methodology (see Figure 2) leads to a comprehensive assessment of the costs and environmental impacts of the integration of smart access devices into the building, enabling the derivation of the carbon payback period.

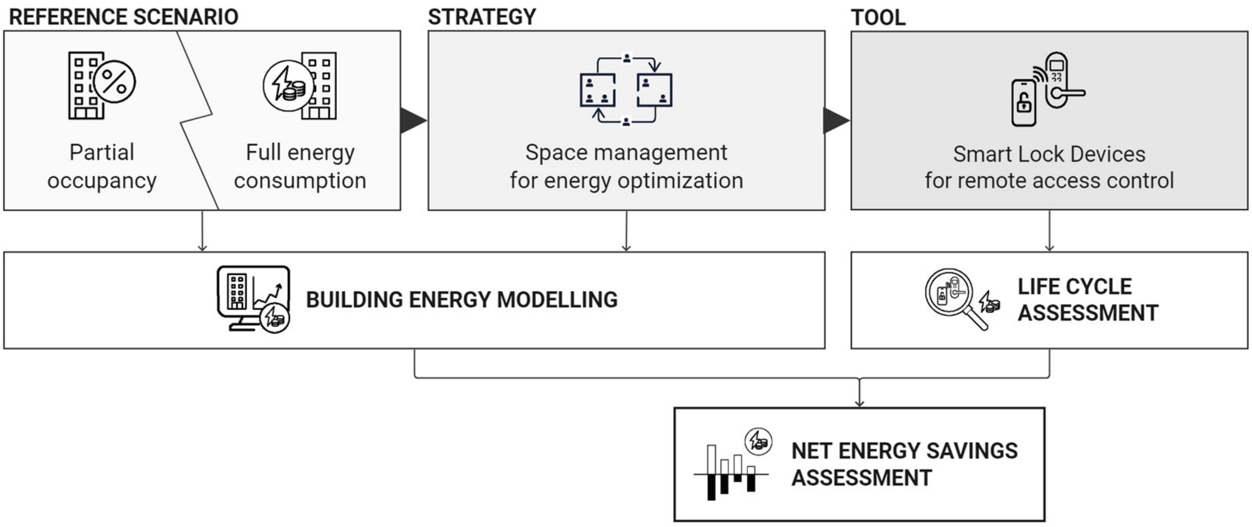


Figure 2. Conceptual methodology workflow: from occupant-centric control strategies to building energy savings assessment. Author's elaboration.

The proposed methodology is applied to a study case described in Section 3.2 and is detailed in Figures 3–5. To optimize various functions within workplace settings, it is crucial to first consider the specific type of office space when developing integrated systems that include door data. The assessment should begin with a geometrical and functional analysis of the building, with particular emphasis on the hierarchy of doors (Section 3.3). This tailored analysis helps determine feasible closure patterns for subsequent stages, including building energy modelling (Section 3.4) and the Life Cycle Assessment (LCA) of the implemented systems (Section 3.5).

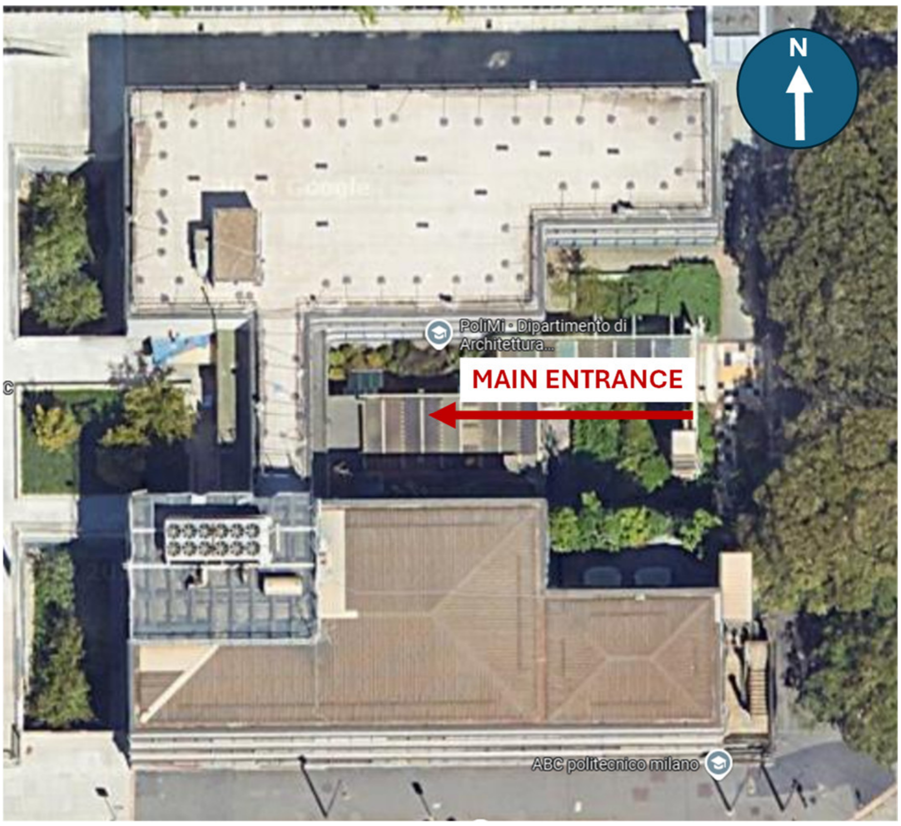
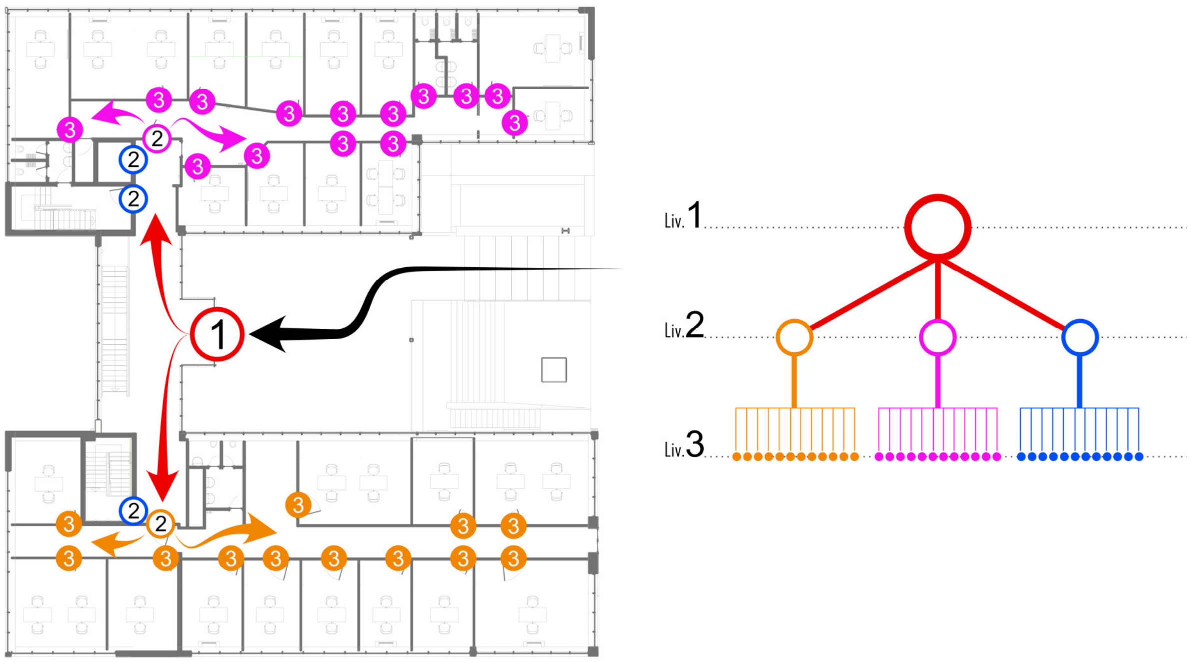
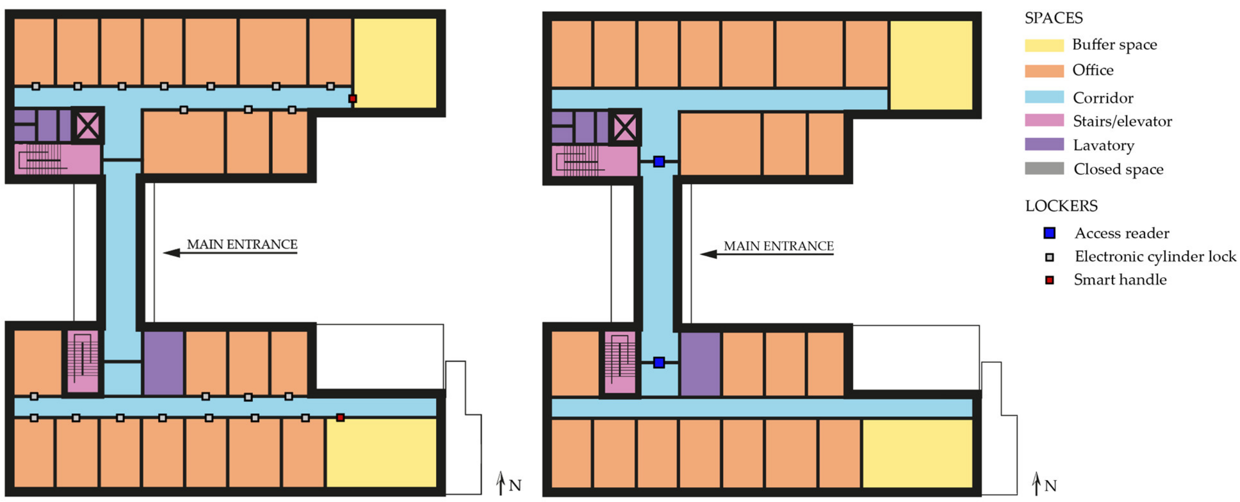


Figure 3. Google street map view of building 15, Department ABC, Politecnico di Milano.



(**a**) (**b**)

Figure 4. (**a**) Ground floor door hierarchy. (**b**) Scheme of door hierarchy levels.



(**a**) (**b**)

Figure 5. (**a**) Baseline device layout. (**b**) Optimized device layout.

3.2. Description of Case Study

The office building studied is part of the Leonardo Campus complex at Politecnico di Milano. The building has an H-shaped design with the two wings aligned East–West, with clear South and North exposure visible in Figure 3. The double façade exposure and potential for partitioning make this orientation an ideal case study for developing and implementing occupant flow management strategies.

The building's total net area is 2821 m^2, with floor heights equal to 3.4 m. As visible in the schematic plans in Figures 4 and 5, the building comprises a basement floor used mainly for maintenance-related activities, three stories above the ground in the South wing and two in the North wing; the two wings are connected by a corridor where the main entrance is located. The building accommodates various activities, with numerous rooms dedicated to the work of professors and researchers of the ABC Department. The building predominantly consists of office spaces and is classified as an office building rather than an educational facility.

3.3. Space Use Strategies Definition

3.3.1. Functional and Access Hierarchy Analysis

To optimize various functions and uses within workplace settings, the development of integrated systems that incorporate door data must first consider the specific type of office space being addressed. The possible office building-use models are listed in Table 1.

Table 1. Office Building-Use Models (OBUM) based on workplace distribution and space organization.

	Standard Model	Activity-Based Model *	CLUB-HOUSE **	HUB and SPOKE **
Presence	100%	Hybrid depends on the assigned activity	0%	100%
In presence activity	all	Meetings, group work, conferences	Meetings	Individual work
Type of spaces	Office rooms Meeting rooms Conference rooms	Meeting rooms Conference rooms	No office building	Satellite offices with assigned workstations

* Hybrid Workplace: Activity-based Office Design in a Post-pandemic Era [1]. ** Places for multi-locational work; opportunities for facilities management [2].

As with most of the office buildings in Italy, the study case building is still managed through a standard space use model, where the offices are supposed to reach 100% occupancy. The definition of a reduced occupancy strategy is effective for office buildings designed to fall into this category.

In the second step, the door hierarchy is considered for the above-ground floors. This approach involves assigning progressive door numbers based on the number of doors required to reach a specific area. Following this structure, the main access door is assigned the lowest number, while subsequent doors leading to different areas within the office space are given higher numbers Figure 4 illustrates the door hierarchy for the case study building.

The door hierarchy analysis helps in understanding people flows within the building, leading to an optimized final smart lock layout. The proposed steps are sufficient to define a feasible smart lock layout (Section 3.3.2) and closure strategy (Section 3.3.3) for the study case building, which displays a clear geometrical division in two opposed wings. A deeper shape analysis should be performed for buildings with a more uniform geometrical plan. The third step for the definition of smart access layout is the analysis of building space functions and occupancy type: these two parameters are necessary to define the flexibility of building spaces. Flexible spaces are suitable for absorbing extra occupancy and allow for people re-allocation when other spaces are closed, and are therefore good choices to become buffer spaces. As visible in Figure 5, the building is composed mainly of offices: ground-floor offices are assigned for planned occupancy, while second and third-floor offices are assigned for variable occupancy. Only two offices on the first floor have flexible workstations and variable occupancy, and are thus eligible to become buffer spaces.

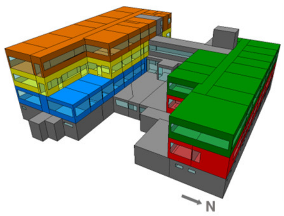
3.3.2. Devices Layout

First, the locking strategy was devised to allocate one lock for each office room, aiming to maximize space flexibility. However, this approach demands a significant initial investment and building modifications. Additionally, considering the building's H-shaped layout, it makes sense to organize spaces based on their seasonal energy use and thermal performances, dividing them into north and south wings. Leaving gaps between closed spaces within the same wing could significantly raise the energy requirements for heated rooms, offsetting the advantages of the space management plan. Through the door hierarchy analysis, it was possible to define the ultimate layout for the devices, which is depicted in Figure 5, and specifically in plan (b).

3.3.3. Closure Strategy

The closure strategy is defined considering the symmetrical shape of the building, which contributes to the distinct exposure and solar radiation conditions of the two wings, and the results of the previously described analysis. The selection of closures is based on the goal of installing a single smart lock per closure, strategically placed to minimize architectural changes while still allowing access to spaces even when they are closed. In conclusion, five closures, referred to as hemi-floor closures, are identified as cost-effective solutions. The location of each hemi-floor, along with its share of the building area and the number of people it accommodates, are detailed in Table 2.

Table 2. Location, building area share and number of people of the 5 hemi-floors and axonometry view of the modelled hemi-floors.

Hemi-Floor	Location	Area Share	Number of People
NF0		11.6%	23
SF0	South wing, ground floor	13.2%	27
NF1	North wing, first floor	11.4%	25
SF1	South wing, first floor	11.7%	25
SF2	South wing, second floor	12.0%	25

3.4. Building Energy Modelling for Closure Patterns Assessment

3.4.1. Building Energy Model and Assumptions

The case study building and the surrounding environment have been modelled in IES-VE [38] to assess the energy use of the current baseline building as well as the potential savings for the strategies implemented. The climatic data for the city of Milan are provided by onebuilding.org. The meteorological data for 1 full year (8760 h) are derived from hourly weather data from 2007 to 2021 using the TMY/ISO 15927-4:2005 [52] methodologies. Appendix A includes charts describing the climatic data for the case study.

BEM input parameters on the building construction have been taken from the energy performance certification carried out in 2007 and are reported in Appendix A (Table A1 for opaque elements, Table A2 for fenestration systems). The study assumes that the building envelope and thermal properties remain unchanged over time.

Given the irregular and unpredictable nature of office occupancy, two reference standards with significantly different assumptions were selected: one with a lower occupancy duration (8 h, as per ISO 17772-1 [53]) and another with a higher occupancy duration (12 h, as per ISO 18523-1 [54]). These standards also account for variations in occupancy density, internal gains (equipment and lighting), ventilation rates, and people density. This dual approach provides a meaningful confidence interval, capturing most occupancy patterns within these two extremes and ensuring robustness in space usage assessments. Such parameters have been summarized and presented in Appendix A (Table A3 for occupants' space use schedules, and Table A4 for internal heat loads). It is assumed that occupants will adhere to the closure strategy as prescribed in the model. Deviations in behaviour, such as unauthorized space use or inconsistent occupancy patterns, are not taken into account of in this study.

Regarding the actual heating and cooling systems in the building, a natural gas boiler and an electric chiller were assumed respectively as generators. These heating and cooling systems have a production efficiency of 0.95 and 2.5, respectively. Likewise, a combined distribution system efficiency rating of 0.82 for both heating and cooling has been assumed, all assumptions based on the Italian National Agency for New Technologies, Energy and the Sustainable Economic Development (ENEA) report for the implementation of EPBD 2020 [3]. The primary energy factors (PEFs) used for evaluating energy consumption are based on current grid conditions, and do not account for potential future decarbonization of electricity production.

3.4.2. Energy Simulations and Comparison Metrics

Remote-controlled doors and access open new possibilities for the optimization of space management; as a starting point, the present work considers only a daily time scale for the optimization strategy.

On top of the baseline of the as-is scenario, the initial assessment involves evaluating energy and cost savings by permanently and alternatively closing each hemi-floor throughout the year. This approach aims to enhance the understanding of the building's response to various closures. Five distinct energy simulation scenarios are conducted (simulations "NF0", "SF0", "NF1", "SF1", and "SF2" in Table 3), with each hemi-floor alternately closed, and the corresponding consumptions for each building layout are calculated.

Table 3. Summary of energy simulations and analysis.

Simulation	Average Occupancy	Closed Spaces	Type
Baseline	100%	none	Dynamic energy simulation
NF0	90%	North wing, ground floor	Dynamic energy simulation
SF0	88%	South wing, ground floor	Dynamic energy simulation
NF1	89%	North wing, first floor	Dynamic energy simulation
SF1	89%	South wing, first floor	Dynamic energy simulation
SF2	89%	South wing, second floor	Dynamic energy simulation
Best closure	89%	Variable, 1 hemi-floor daily	Data processing
89% distributed	89%	none	Dynamic energy simulation

A dynamic closure strategy is established by selecting the least consuming closure layout each day from five simulated options to optimize building energy use (refer to the "Best closure" simulation section). This selection is based on a comparison of energy consumption data from the simulations, while a new dynamic energy simulation incorporating the chosen closure pattern will be part of future project steps. Due to the absence of real data on occupancy, the best closure is defined as the maximizing of energy savings without consideration of the number of available/needed seats.

Finally, an additional simulation is conducted to better understand the impact of occupancy reduction on building energy consumption. Daily closure of one hemi-floor reduces the building's capacity by an average of 11%. Consequently, the building is remodeled, with all accessible spaces having a distributed occupancy of 89% compared to the baseline. The results of the "89% distributed" simulation are then compared to the building's performance with the applied closure strategy to assess the effect of reduced occupancy.

3.4.3. Comparison Metrics

The performance of each occupant flow management strategy is evaluated based on the following metrics:

Primary Energy

Allows the assessment of the building's overall impact and allows comparison with any other building. Additionally, it facilitates the computation of energy-related costs, savings, and carbon emissions. Primary Energy Factors (PEFs) are selected for Milan, Italy from those reported by ENEA [3] and are reported in Table 4.

Table 4. PEF for energy carrier.

Energy Carrier	Non-Renewable PEF	Renewable PEF	Total PEF
Natural gas	1.05	0	1.05
electricity	1.95	0.47	2.42

Energy Use per Person

A second key indicator is the Energy Use per Person (*EUP*) defined as the yearly primary energy use of the building (PE_{year}) divided by the sum of occupants (N_{people}) in the building (kWh/person year) (Equation (1)).

$$EUP = \frac{PE_{year}}{N_{people}} \quad (1)$$

This metric is used to facilitate comparison among closing strategy scenarios: energy can be normalized by the number of users to understand the efficacy of the closure strategy.

3.5. Life Cycle Assessment

3.5.1. Scope of Assessment and System Boundaries

The objective of the assessment over the life cycle of the building is to evaluate the embodied carbon and energy invested in the materials and processes of the systems and components used for access management for the offices and co-working spaces of the case study building described in Section 3.2. In particular, a comparative life cycle assessment (LCA) is made of the two alternative configurations for the automated access management system, i.e., "Base device layout", which is based on a large use of electronic devices for smart access, and "Optimized device layout", which minimizes the number of smart devices and adopts a conventional mechanical system with brass cylinders and key insertion.

For the life cycle assessment under the two scenarios considered, a quantitative analysis was carried out based on the measurement of the two main environmental impact categories which are taken into account, namely Global Warming Potential (GWP100), which is used to assess the value of kg $CO_{2\text{-eq}}$, and Cumulative Energy Demand (CED). The ISO Standards 14064 [55] as well as the EN 15804 [56] were used as reference approaches for the LCA. The boundaries of the system include the two major phases which influence the results on the base of the goal set: (i) extraction and production phase (A1–A3) and (ii) maintenance and replacement (B2–B4). In module A1–A3 (product stage), the phases of raw material extraction are detailed.

3.5.2. Primary Data Collection and Modelling of Device Production

In the production phase (A1–A3), the specific emission factors and embedded cumulative energy of the processes for producing the devices and complementary components used under the two configurations were assumed from secondary data contained in the ecoinvent 3.8 database [1,57] and modelled within LCA software SimaPro 9 [2,58]. Data from material processing, transportation and waste generation and treatment of the two devices used as locks, namely a conventional mechanical system and smart lock, were collected directly from a production plant located in northern Italy, while all other components used in the infrastructure layout were assumed as an assembly from the ecoinvent dataset. All primary data collected for each process are categorized according to a coding system, and for each code a hierarchical level is assigned. The highest level corresponds to products not yet processed, while the lowest level corresponds to the finished product, with production which takes place outside the manufacturing space. In the mechanical cylinder, the number of levels is seven, while in the electronic case, the number is nine. Moreover, for each code, a nomenclature is assigned to distinct items purchased from an external company, on-farm manufacturing, and accessories (e.g., labels, screws, instruction booklet, etc.). According to the code, and depending on the level analyzed, an indication of the location of each supplier was assumed for modelling the transportation. Generally, supplied products were considered as having been moved via roads by trucks with a load capacity of up to 16 tons. Additionally, an optimized delivery process was assumed to model the transportation phase in A2, validated by the company as best practice. Specifically, it was assumed that all vehicles arriving at the manufacturing center to deliver externally processed products are also in charge of collecting the sub-products to be processed by third parties. Consequently, return travel with an empty volume is avoided. On the other hand, empty return travel was assumed for all raw materials and non-processed materials by third parties.

The number of processed materials in each level was then assigned to the devices, and an allocation method by mass was used to allocate loads from energy and water use by machinery and from waste generation and treatment, as well as benefits from material recycling and onsite renewable energy generation by solar panels. Specifically, for machine-related energy absorption, the estimation of the total hours of machine use for each machining operation was assumed. Then, for each level of analysis, the number of processed parts was associated with the number of hours of process duration. Finally, the energy input for each machinery process was assessed from the apparent power generated by each machine, measured in kilovolt Amperes (kVAs), which expresses the sum of real and reactive power, multiplied by a standard power factor for a three-phase generator equal to 0.8, and the numbers of hours needed for each machinery process.

For the allocation of loads from the liquid waste of each processing phase, the analysis breaks down differently for the two main devices and their components, such as the mechanical cylinder and electronic lock. Liquid waste refers to the amounts of alcohol and oil absorbed during the process and expected to be disposed of at the end of the process. From the analysis of the data available, the exact amount of liquids used in the two processes was derived. Then, in order to allocate the generalized consumption of liquid for each process, the amount of water was divided by the number of pieces processed per hour while, since the quantities of oil and alcohol were given over a monthly period, the total amount of liquid was allocated considering two eight-hour working turnovers.

3.5.3. Inventory of Materials and Processes for Device Installation and Management

The application of the locking system to the case study under the two different configurations, base device layout and optimized device layout, requires very different layouts and the design of two different infrastructures, as presented in Section 3.3.2. Except for smart locks and mechanical cylinders, which required a specific life cycle inventory (LCI) modelled from primary data collected, as described in Section 3.5.2, due to a lack of data in the LCA databases, all other devices needed to manage access to the building were modelled from secondary data available in ecoinvent. For both scenarios, they include (i) the multi-standard wall-mounted reader, (ii) the electronic handle with access reader, (iii) the gateway, which is a device that connects the cloud platform with the lock, (iv) the controller, which is a device management server, and (v) the actuator for the electronic lock. The complete list of materials and processes used for installing the two systems in the case study building and the functional unit (FU) adopted to run the LCA model is reported in Table 5.

Table 5. Materials and processes adopted from ecoinvent dataset to model the devices and infrastructure for access control installed in the case study.

Materials/Assemblies and Processes	FU	Base	Optimized
Smart lock	p	69	7
Mechanical cylinder	p	-	69
Cable, unspecified {GLO} | cable production, unspecified | Cut-off, U	kg	20.9	14.7
Switch, toggle type {RoW} | switch production, toggle type | Cut-off, U	kg	0.99	0.99
Router, internet {CH} | router, internet | Cut-off, U	p	10	6
Electronic component, passive, unspecified {GLO} | electronic component production, passive, unspecified | Cut-off, U	kg	5.4	5.4
Electronic component, passive, unspecified {GLO} | electronic component production, passive, unspecified | Cut-off, U	kg	6	6
Steel, chromium steel 18/8 {RER} | steel production, electric, chromium steel 18/8 | Cut-off, U	kg	5	5
Battery cell, Li-ion, NCA {RoW} | battery cell production, Li-ion, NCA | Cut-off, U	kg	0.24	0.24
Electricity, medium voltage {IT} | electricity, medium voltage, residual mix | Cut-off, U	kWh	0.07	0.03

The model was planned to carry out under a time horizon of 20 years, which is considered representative of the expected service life of the locking system under conventional use. All the gateways installed in the building were assumed to be replaced every 10 years, while the batteries were assumed to be replaced every 5 years, as prescribed by the main providers available. The type of battery used by the smart locks is the CR123A 3V, with a gross mass of 17 g each, while three AAA batteries weighing 8 g each are required for smart readers. All other electronic devices used to connect the infrastructure are supposed to be cable-connected. The complete scheme of the infrastructure layout is shown in Figure 6.

In addition to the main components, the LCA model takes into account the contribution of the electrical wires needed to connect the different devices. Particularly, three types of cables were considered, i.e., power supply, with a linear mass density of 21 g/m, LAN, with a linear mass density of 45.2 g/m, and POE with a linear mass density of 61 g/m.

The total mass of cables as well as the length for each wiring category on each floor are reported in Table 6 for the base device layout, while the mass and length of electric cables for the optimized device layout are collected in Table 7. All values are increased by 20% to take into account of the generation of waste during onsite operations.

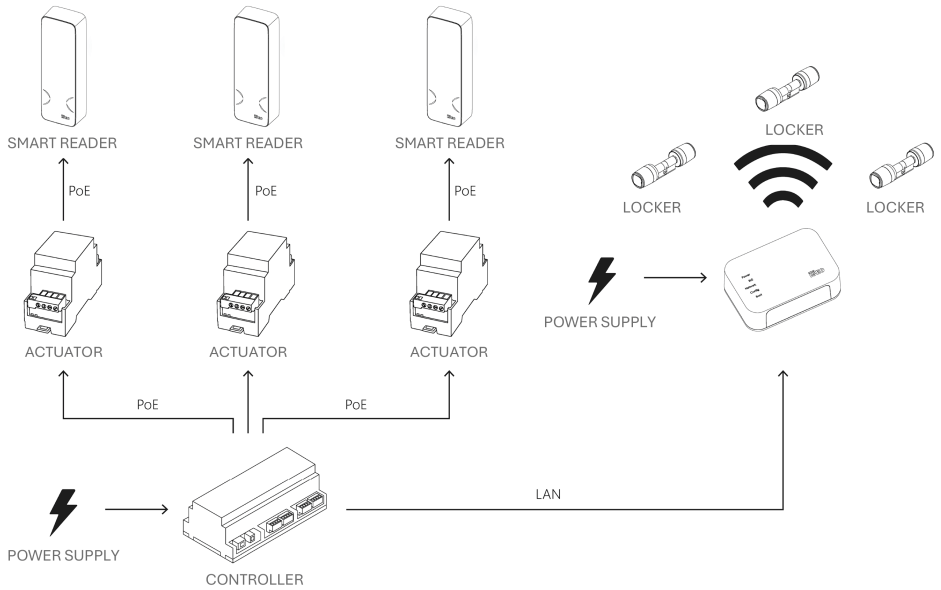


Figure 6. Scheme of the connection of the different devices used in the infrastructure of the smart locking system applied in the case study.

Table 6. Connection cables for devices installed on each building floor for the Base device layout scenario.

Floor	Power Supply		LAN		POE	
	L [m]	Mass [kg]	L [m]	Mass [kg]	L [m]	Mass [kg]
F-1	51	1.1	51	2.3	57	3.5
F0	39	0.8	39	1.8	33	2.0
F1	39	0.8	39	1.8	33	2.0
F2	42	0.9	42	1.9	33	2.0

Table 7. Connection cables for devices installed on each building floor for the Optimized device layout scenario.

Floor	Power Supply		LAN		POE	
	L [m]	Mass [kg]	L [m]	Mass [kg]	L [m]	Mass [kg]
F-1	12	0.3	12	0.5	57	3.5
F0	12	0.3	12	0.5	33	2.0
F1	12	0.3	12	0.5	33	2.0
F2	42	0.9	42	1.9	33	2.0

4. Results

Following the shape and functional analysis, smart locks are implemented in the case study office building as an enabling technology. These locks facilitate the operation models previously identified, allowing for the partial shutdown of building functions. The results, including energy savings and environmental impact, are detailed in this section. The findings are combined to provide a final assessment of energy, carbon and cost savings and the return time of the investment in terms of carbon emissions.

4.1. Building Savings Assessments

As a first outcome of the study, this section delves into the essential parameters for designing a compartmentation strategy: the occupancy profiles and the internal gains, the location and space function of the building rooms, and the weekly trends in energy consumption. Comprehension of the relationship between the bespoke factors is essential for the development of guidelines for future applications of the study. The best closure layout strategy is defined daily; the savings in terms of costs and carbon emissions are quantified demonstrating the effectiveness of the proposed methodology for a real office building.

The baseline building global Primary Energy consumptions and related costs, following the proposed methodology, are reported in Table 8.

Table 8. Baseline Building Annual Primary Energy Consumption concerning different occupancy and use standards.

Standard	PE [MWh]
ISO 17772-2 [53]	435.8
ISO 18523-1 [54]	867.2

The share of energy use per type is detailed in Figure 7.

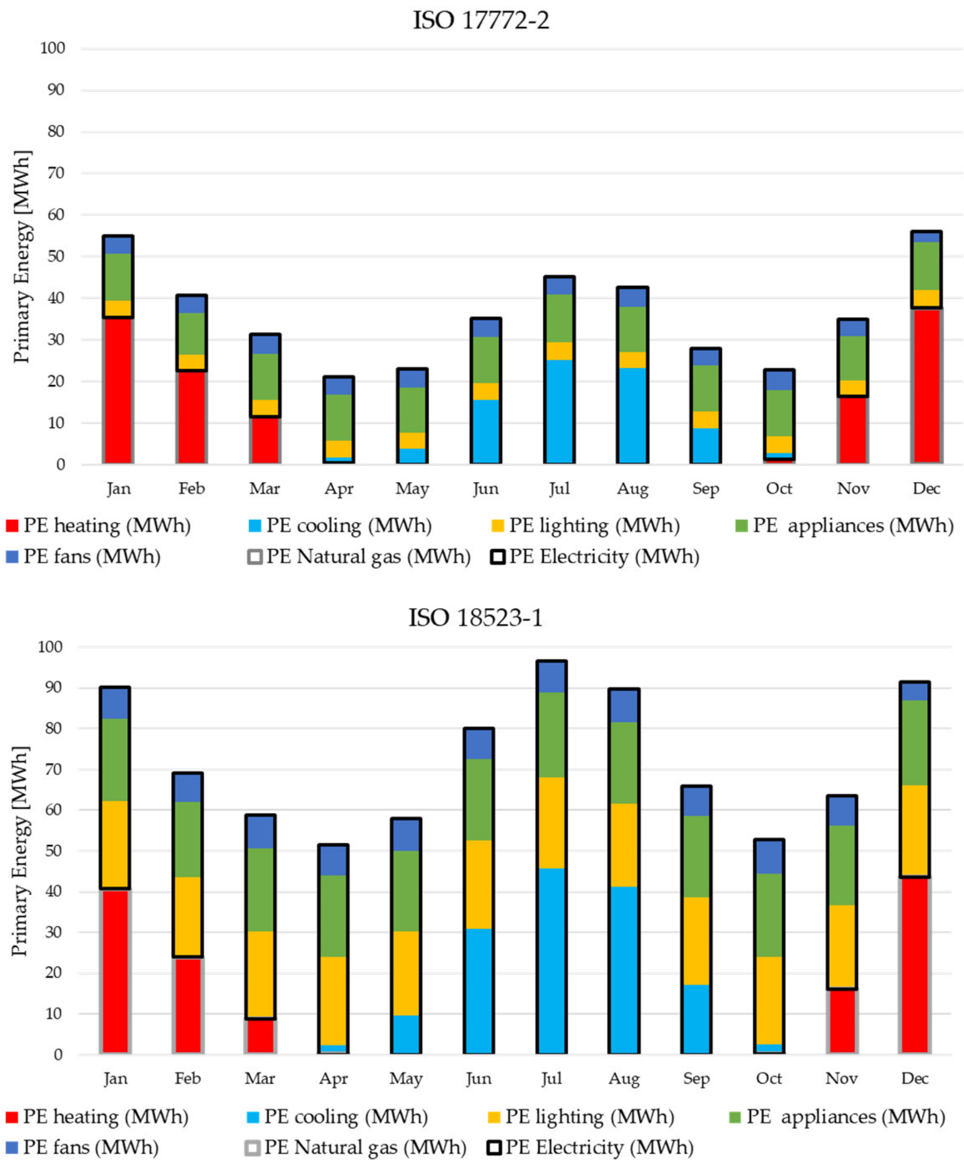


Figure 7. Primary Energy for energy consumption and energy carrier following standard ISO 17772-2 [53] (**top**) and ISO 18523-1 [54] (**bottom**).

The four hemi-floors are comparable both in terms of space, people and annual savings, which range from a minimum of 9.1% for closure SF1 to a maximum of 12.2% for closure SF2 considering ISO 17772-2 [53]. Figure 8 shows the annual savings for each closure strategy for both standards and assuming an annual closure for each hemi-floor for the sake of comparison. The daily savings values should be considered to maximize the savings potential of the closure.

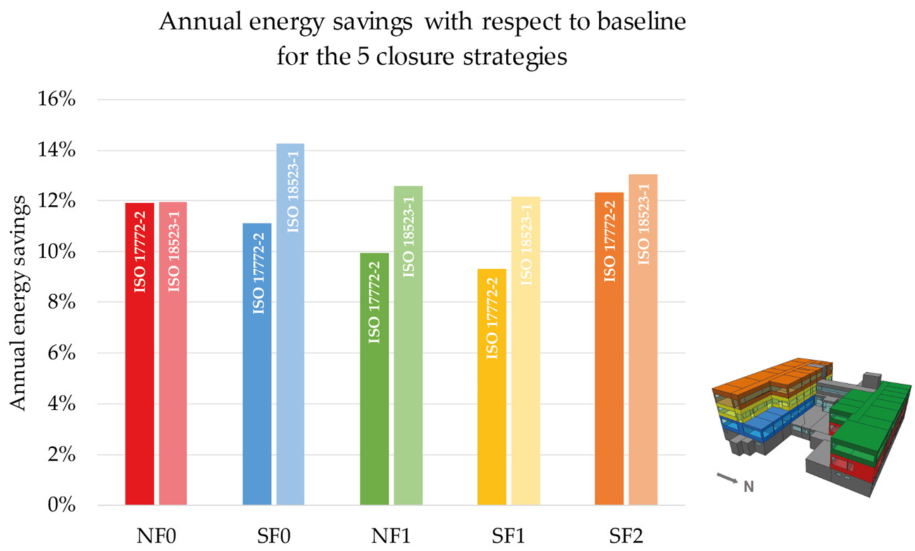


Figure 8. (**left**) Annual saving share for each closure possibility; (**right**) axonometry view of the modelled hemi-floors.

A dynamic and remote-controlled lock gives the possibility of exploiting the building characteristics to maximize savings, which were first presented in Figure 8 considering the same hemi-floor as constantly closed during the year. In Figure 9, the variability of daily savings during heating and cooling seasons is presented. Considering the results obtained with ISO 18523-1 [54], the savings due to the closure of any hemi-floor during the cooling season are always higher than the savings recorded during the heating season: the extended occupancy schedule has a high impact on the simulated internal loads for ISO 18523-1 [54], resulting in an energy-expensive cooling season.

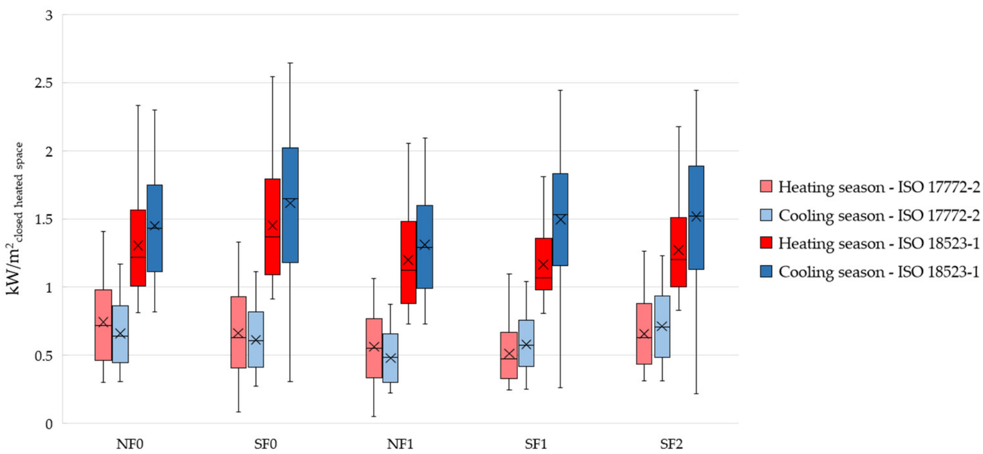


Figure 9. Distribution of daily savings during working days for each closure strategy following ISO 18523-1 [54] and ISO 17772-2 [53].

Moreover, the closure strategies related to south wing hemi-floors obtain a wider range of savings, reaching a difference in daily savings of 0.91 kWh/m^2 for SF2. The lowest energy savings, gained when closing the south wing second floor (SF2), are scored on the 28th of April (0.31 kWh/m^2), and the maximum daily savings on the 3rd of August (1.22 kWh/m^2): the increased internal loads contribute to thermal comfort during midseason, while they should be balanced during summer.

Regarding ISO 17772-2 [53], the north wing average savings are always higher during the heating season. The south ground hemi-floor follows the same trend, having an average possible saving of 0.66 kWh/m^2 during the heating season and 0.60 kWh/m^2 during the cooling season. The reason for the differences in trend between the south ground floor and the other south floors can be found in the number of exposed surfaces and their stratigraphy. In general, a performative closure strategy should be defined daily.

Due to the absence of real data on occupancy, the best closure is defined as the maximization of energy savings without consideration of the number of available/needed seats. The distribution is studied for the two standards that are considered as minimum and maximum occupancy. The chart is created by combining the results of the single simulations ("Best closure" simulation). Clearly, mid-season registers the lowest benefit from the closing strategy while, in extreme temperature periods, the savings are higher, reaching a maximum of 2.64 kWh/m^2 on the 3rd of August; a similar value of 2.54 kWh/m^2 can be saved by closing south wing ground floor (SF0) for the 5th of January.

Regarding simulated energy consumption, it is possible to determine daily closures of the hemi-floor which leads to the greatest energy savings. The following graph (Figure 10) shows the maximum achievable energy savings based on the time of year and usage profile, compared to the two standards analyzed, which were selected to represent the building's highest and lowest occupancy levels. The chart is created by combining the results of the single simulations ("Best closure" simulation) per day.

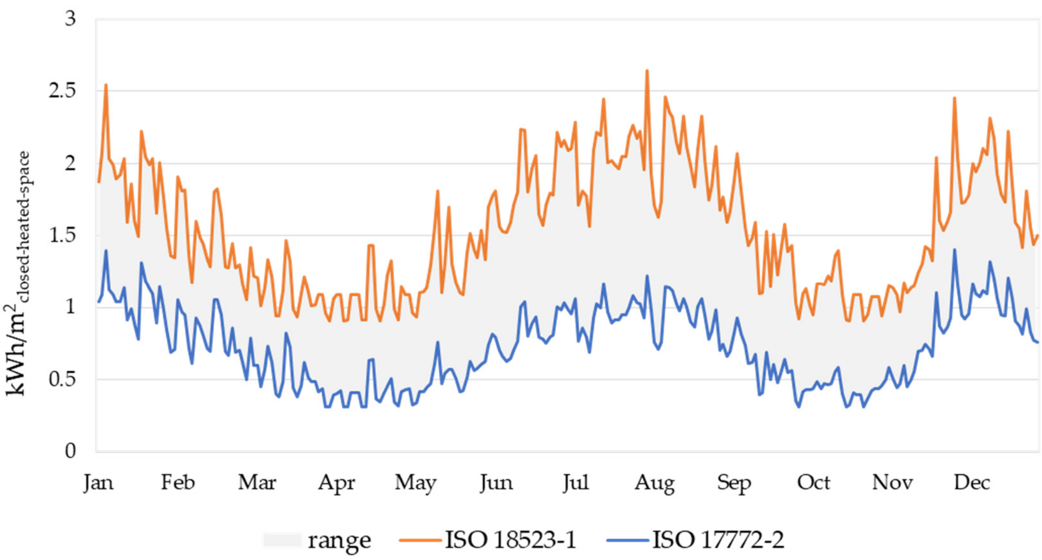


Figure 10. Annual distribution of daily cost savings choosing the best performative closure.

The corresponding best hemi-floor closure for each day of the year is reported in Figure 11. Considering ISO 18523-1 [54], the optimization strategy is dominated by the closure of SF0, both in the heating and cooling seasons. Appendix A provides some insights into the external conduction losses of the South ground floor, which are responsible for the high consumption, or savings when closed, of this hemi-floor. Instead, ISO 17772-2 [53] model gives a mixed closure distribution: the two ground hemi-floor closures alternate during the cooling season, while SF2 is prevalent in summer due to the high exposure to solar radiation of this hemi-floor.

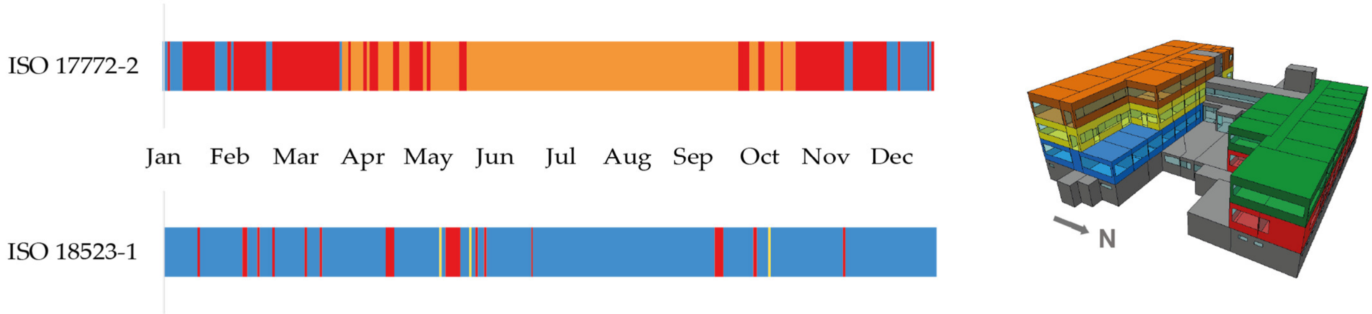


Figure 11. (**left**) Annual distribution of best closure choice. The color of each bar is representative of the color of the hemi-floors in part b of the figure, clearly underlining the hemi-floor closed over the timeline; (**right**) axonometry view of the modelled closures (hemi-floors).

Each year the defined configuration leads to a total amount of savings of around 13% for both standards. The total savings are reported in Table 9 in terms of primary energy.

Table 9. Total annual savings with the defined best closure.

Standards	Baseline Annual Consumptions [MWh]	Annual Savings with "Best Closure" Strategy	
		MWh	%
ISO 17772-2 [53]	435.78	56.1	12.88
ISO 18523-1 [54]	867.00	123.3	14.22

These savings can be obtained with an 89% occupancy, i.e., 25 people at home, when 237 people account for the full capacity of the building (Table 10). In conclusion, the annual Energy Use per Person is computed considering an 89% occupancy distributed across the whole building and 89% occupancy considering the best closure distribution previously highlighted.

Table 10. Comparison between occupancy scenarios.

Standards	Simulation	Occupancy	Total PE [MWh]	EUP [MWh/Person]
ISO 17772-2 [53]	Baseline	100%	435.78	1.85
	89% distributed	89%	425.19	2.10
	Best closure	89%	379.64	1.79
ISO 18523-1 [54]	Baseline	100%	867.16	3.68
	89% distributed	89%	827.61	3.90
	Best closure	89%	744.04	3.51

During the closure, the EUP decreases by 10% with respect to the same occupancy without a people management strategy.

4.2. Cumulative Energy Demand, GWP and Carbon Footprint over the Life Cycle

4.2.1. Cumulative Energy Demand and GWP of Conventional Locking System vs. Smart Lock

From the primary data collected and the elaboration of the inventory of energy, materials and waste tracked at the manufacturing stage, the LCA of the two main locking devices, the mechanical cylinder and the electronic lock, were performed and the results were compared. As shown in Figure 12, the production from cradle to gate of the mechanical cylinder generates an emission of 2.3 kg CO_2-eq per piece. This includes the production of all mechanical components, keys (three copies per device) and packaging.

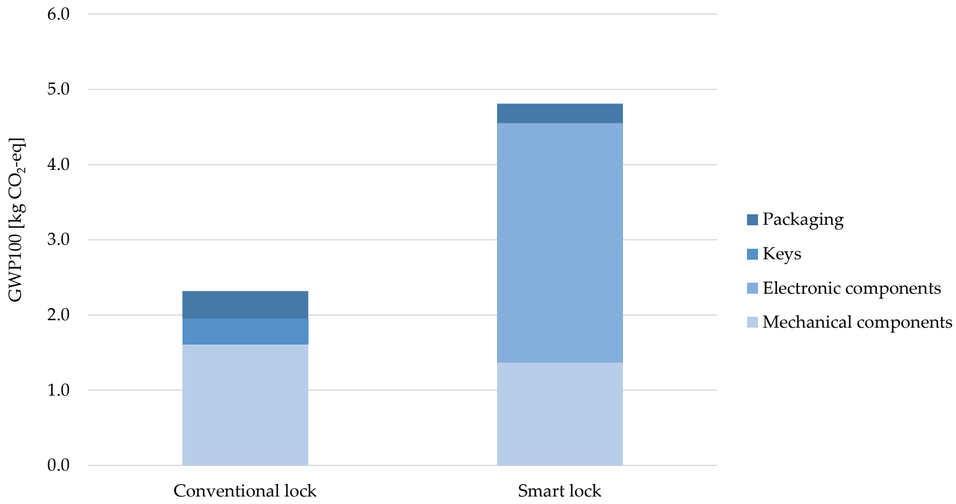


Figure 12. Global warming potential (GWP-100) of the conventional lock (mechanical cylinder) vs. smart lock (electronic locking device).

Nearly 70% of the carbon emission is allocated to the production of the metallic cylinder, where brass processing is the major contribution to the share. An additional 15% of carbon emission is generated by the key production and waste generated by steel processing. Finally, the packaging used to store and sell the product contributes an additional 15% of the total emission, with a large contribution of carton paper used for the product cover. Since brass processing is dominant, and a large amount of residue is generated during production, the recovery of brass at the end of the life of the product is an essential step to be tackled in order to implement circularity in the value chain and reduce the overall carbon footprint of the device.

In contrast, the electronic device used as a smart locking system achieves a total emission of 5.7 kg CO_2-eq, which is around 2.5-fold the carbon intensity obtained from the mechanical cylinder. The result is heavily influenced by the large presence of electronic components, with production involving carbon-intensive processes and assemblies. The contribution of the electronic components is dominant, with nearly 3.2 kgCO_2-eq emitted, which corresponds to 66% of the total share. More than 47% of the carbon emission is caused by the rotor, which dominates the share of the electronic components, along with the sole electronic board, which contributes to 16% of the total share. The mechanical processes for the fabrication of the mechanical components play a minor role, with a contribution equal to 28%. Finally, a marginal contribution is registered for the packaging, with a share of 5%.

In Figure 13 the results of cumulative energy demand (CED) are shown. For both cases, the contribution of non-renewable energy is dominant and much larger (almost 5-fold more in the case of the smart lock) than that caused by renewable energy.

In the case of the conventional lock, the dominant contribution, both renewable and non-renewable, is caused by mechanical components (between 69–71% of the share), while both packaging and key production contribute to an additional 14–16% each. In contrast, for smart lock production, the main energy need is registered for the electronic component's fabrication, which requires nearly 16 kWh of non-renewable energy and roughly 2.5 kWh of renewable. Next are the mechanical components, with a relative share of 25–20%, and finally the packaging, with a marginal contribution of 4–10% to the global cumulative energy demand.

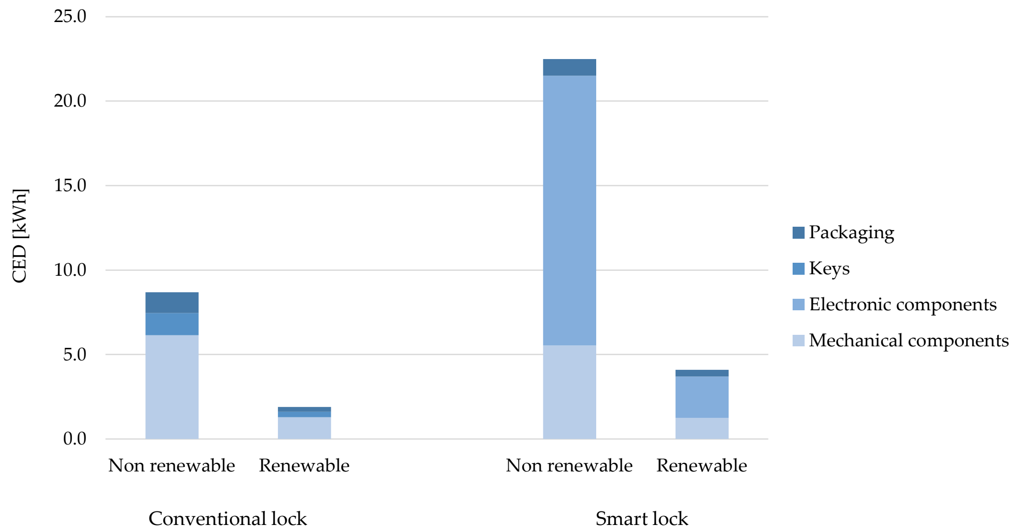


Figure 13. Cumulative energy demand (CED) of the conventional lock (mechanical cylinder) vs. the smart lock (electronic locking device).

4.2.2. Carbon Footprint of Conventional Locking System vs. Smart Lock

At the building scale case, the carbon footprint of all devices and connections needed to run the locking system was estimated and carbon emissions summed up for carbon savings from the operational energy saved by the monthly flow optimization of users, according to the two affluence standard scenarios, assumed and described in Section 3.4.1. The cumulative embodied carbon and the cumulative operational carbon saved by implementing a smart lock system under a base device layout on the building case study are shown in Figure 14. In the life cycle assessment carried out, four main time laps over 20 years of service life were evaluated. At year 1, i.e., time of installation, the only contribution is related to the embodied carbon of the installed components, which account for around 2 tons of CO_2-eq. After 5 years of usage, the carbon savings from operational energy optimization show a significative dominance, with around 196 tons of CO_2-eq saved in case of affluence according to ISO 18523-1 and around half-savings, equal to 82 tons of CO_2-eq in case of affluence according to ISO 17772-2. Even considering the maintenance operation of the management system, as well as the replacement of exhausted electronic components and batteries, the cumulative carbon savings increase nearly linearly at every step, with a total saving which increases in the case of ISO 18523-1 from 444 tons of CO_2-eq after 10 years of use to 940 tons of CO_2-eq after 20 years from the installation. Similarly, in the case of ISO 17772-2, the total cumulative savings increase from a range of 187 to nearly 400 tons of CO_2-eq in 10 years.

Finally, the cumulative carbon savings under the two alternative configurations, base and optimized, are compared and the results are visualized in Figure 15. According to ISO 18523-1 [54], moving from a base device layout, which consists of installing 69 smart locks in the building case study, to an optimized scenario, with a reduction to just 7 pieces, brings a carbon reduction equal to 0.66 tons of CO_2-eq at the time of installation. After 5 years, a marginal difference between the two layouts is registered, mainly due to the replacement of the batteries of the devices and the lower amount of electricity needed by the system. After 10 years from installation until the end of life, the gateways are assumed to be replaced with new ones, and this avoids emission in the case of the optimized device layout, with a relative saving of nearly 1.5 tons of CO_2-eq in the case of ISO 18523-1 and roughly 1.8 tons in the case of ISO 17772-2 [53].

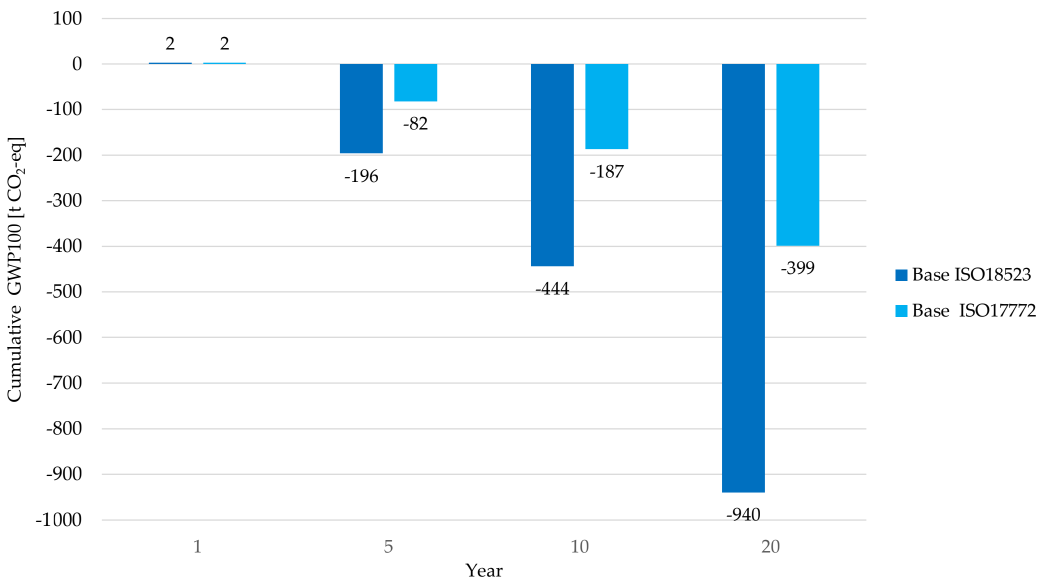


Figure 14. Cumulative carbon saving potential, estimated as a sum of the embodied carbon for installation of the smart locking system, under the base device layout, and the saving from energy optimization due to the flow of users' management during 20 years of service life of the building.

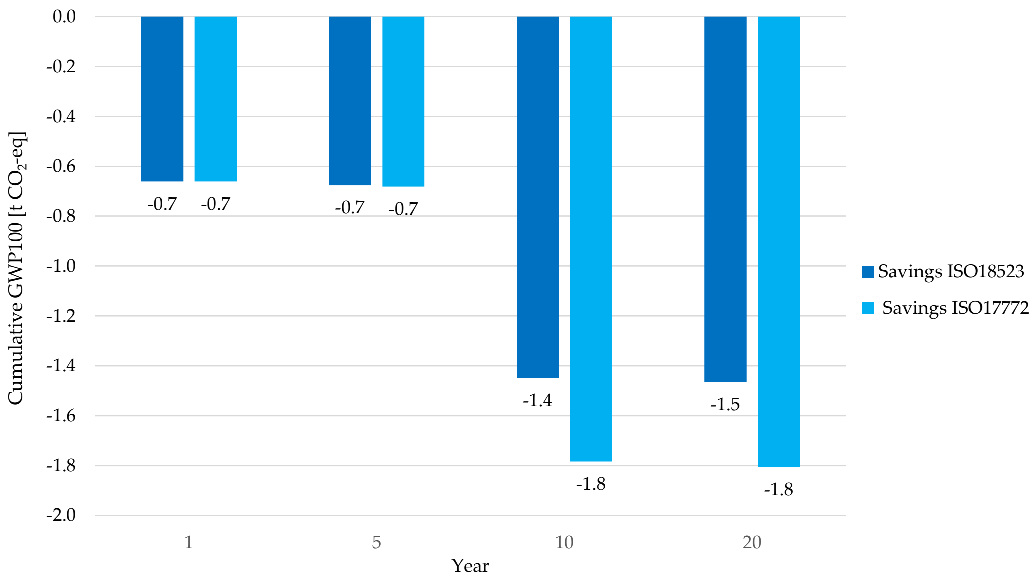


Figure 15. Relative carbon savings between the two analyzed configurations (base device layout and optimized device layout) for the two standard alternatives considered for assessment.

5. Uncertainties, and Limitations of the Study

This study is based on a simplified building operating model due to the absence of detailed data on actual usage profiles. To address this, we applied widely used occupancy standards (ISO 17772-1 [53] and ISO 18523-1 [54]), which provide a structured framework for estimating occupancy patterns, internal gains, ventilation rates, and lighting requirements. The study also assumes a uniform office-like usage pattern, making it more applicable to environments that allow functional adaptation, shared workspace management, and desktop-based work setups (e.g., co-working spaces). The absence of real-time occupancy tracking introduces uncertainty in estimating potential energy savings, as deviations from the assumed occupancy patterns could impact the strategy's effectiveness. The study provides an in-depth evaluation of a selected set of closure configurations, offering valuable insights into their performance. While a full sensitivity analysis across all possible closure combinations is beyond the current scope, this work lays a strong foundation for future research. Expanding the approach to incorporate dynamic optimization with real-time data and occupant preferences could further enhance adaptability and efficiency. Additionally, the estimation of primary energy use and operating costs relied on standard methodologies, which, while effective for broad assessments, may not capture all the specific operational characteristics of a given building. While the methodology can be applied to other buildings, the specific findings, such as absolute energy savings, cannot be directly extrapolated to different building typologies without further validation. Future reductions in the carbon intensity of the national energy mix could also influence the projected energy savings, though this is an inherent uncertainty in long-term energy planning. Furthermore, variations in HVAC system efficiency and potential regulatory changes, such as stricter energy performance standards or incentives for occupancy-based energy management, could influence the strategy's applicability and cost-effectiveness.

Finally, a life cycle assessment (LCA)for electronic devices was conducted using general data from the ecoinvent database. While this provides a reliable approximation, regional variations in manufacturing and usage patterns could slightly affect the precision of the life cycle carbon footprint analysis. Potential variations due to different manufacturers, battery replacement cycles, or alternative access control technologies are not fully examined. Additionally, uncertainties arise from factors such as occupancy variation and energy consumption fluctuations

6. Conclusions

This study highlights several key strategies for optimizing building energy efficiency and improving occupant comfort.

Where direct interventions on the building envelope and services may not always be feasible, in such cases we propose lean strategies, which still lead to significant energy savings by optimizing space use and building management. The results for the case study building suggest that a 13% energy-cost saving is reached through the implementation of a dynamic closure strategy for both modelling choices. However, the results for building energy class following ISO 18523 [54] suggest that people management strategies can optimize energy use but should not be considered as solution strategies for buildings with extremely poor energy performance. The savings correspond, in terms of CO_2 emissions, to 7.5 and 17.6 $kgCO_{2eq}/m^2$, respectively.

A central recommendation is to adopt the concept of door hierarchy. By organizing building spaces according to this hierarchy, closures can be aligned with designated groups, making the layout more intuitive and functional, which in turn enhances overall efficiency.

Another important strategy involves careful selection and sizing of buffer spaces. These spaces should be chosen based on their energy efficiency characteristics and should be sized to provide the desired level of adaptability. This ensures that the building can respond effectively to changing needs while maintaining energy efficiency.

Occupancy profiles are inherently uncertain but are critical for determining a building's energy performance. By using strategic space management techniques, it is possible to anticipate and influence how people move within the building, optimizing space use and reducing energy consumption. The energy modeling approach does not incorporate advanced building automation systems (BACS) or occupancy-based controls (e.g., PIR sensors). While such systems could enhance energy efficiency through automated shutdowns and space optimization, our focus was on evaluating management strategies that do not rely on pre-existing automation. However, integrating smart locks and app-based user interactions could further enhance the adaptability of the proposed approach.

The exposure features of a building offer a valuable opportunity to enhance energy efficiency. For example, during winter, grouping occupants in south-exposed areas can take advantage of natural sunlight to reduce heating needs. In summer, placing people in north-exposed areas can help keep space cooler and reduce the need for air conditioning.

It is also important to identify spaces that are overly exposed or poorly insulated. These areas are often the best candidates for closure or additional insulation, which can prevent energy loss and improve the building's overall performance.

Finally, closure plans should be tailored to the building's weight classification. For medium or heavyweight buildings, weekly closures can help maintain thermal stability, while lightweight buildings, which are more susceptible to temperature changes, may require daily closures.

The smart lock system, when integrated into an office building that allows partialization and local shut-down possibilities, could offer significant carbon savings through optimized management of occupant flows and energy use. Over a 20-year service life, cumulative carbon savings can be substantial, particularly in scenarios where user flow is carefully managed according to standardized occupancy profiles (ISO 18523-1 [54] and ISO 17772-2 [53]). Even after accounting for maintenance, component replacement, and energy use, the smart lock system demonstrates an advantage in reducing the building's overall carbon footprint as part of a strategy for improving energy efficiency, especially in existing buildings with limited possibilities for improvement unless deep renovation interventions are made.

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Appendix A

Appendix A provides additional information about building energy modelling; specifically, Figures A1 and A2 show the DBT and radiation values for the case study, respectively, Table A1 reports U-values of opaque elements, and Table A2 for glazed systems;

Table A3 gives a summary of the occupancy schedules with the related internal gains; and Table A4 provides the values for other internal loads.

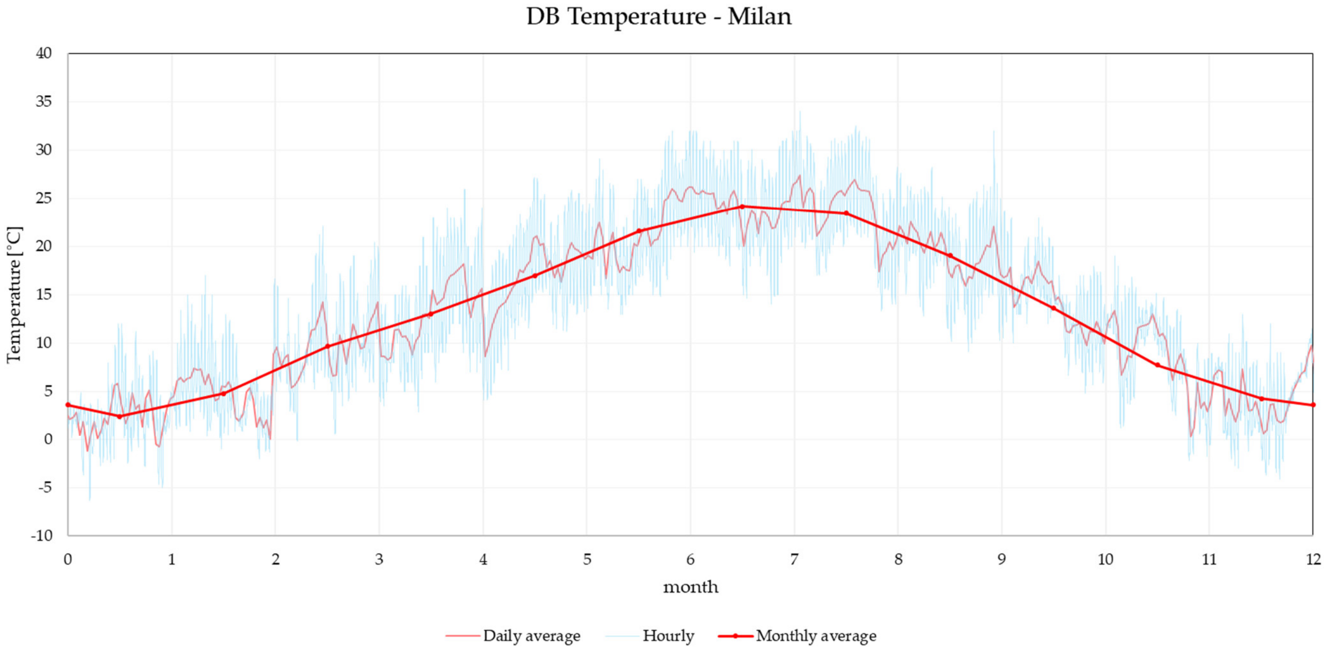

Figure A1. Dry Bulb Temperature in Milan (EnrgyPlus Weather Data provided by onebuilding.org). Comparison between hourly data and daily and monthly moving averages.

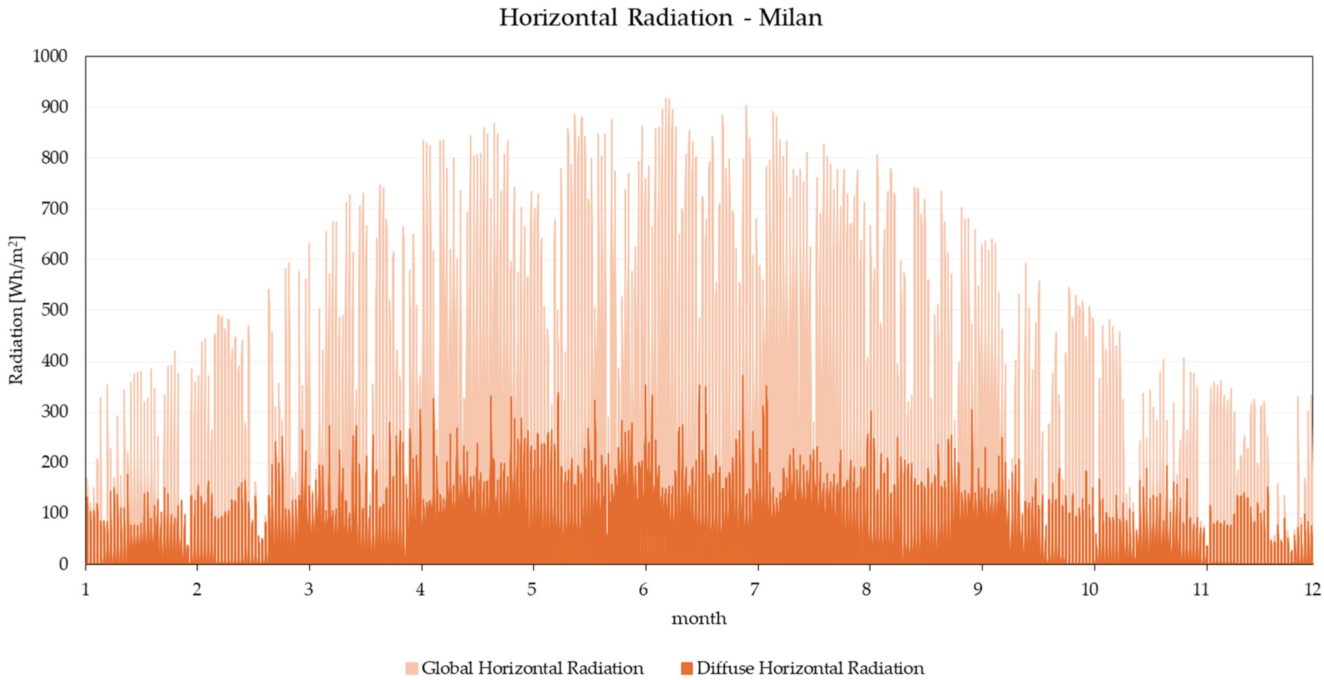

Figure A2. Hourly Horizontal Radiation in Milan (EnrgyPlus Weather Data provided by onebuilding.org). Global and diffuse radiation values.

Table A1. Building constructions.

Element	Stratigraphy	U-Value (W/m^{2}K)
External wall 1	Plaster + reinforced concrete + ceramic tiles	2.51
External wall 2	Plaster + perforated clay bricks + ceramic tiles	1.07
External wall 3	Plaster + unreinforced concrete + cement coating	1.53
Roof 1	EPS + air gap + corrugated steel sheet	0.36
Roof 2	EPS + membrane + gravel	0.34
Ground exposed slab	Gravel + lightweight concrete + cement + stoneware	1.26
Internal slab	Brick-concrete slab + lightweight concrete + tiles	1.32
Internal partition	Plasterboard + air + plasterboard	1.79

Table A2. Glazing systems.

Element	Stratigraphy	g-Value	U-Value (W/m^{2}K)
Double-glazed unit	6mm clear float + 12 mm air + 6 mm clear float	0.71	2.63

Table A3. Occupancy schedule and gains for the building rooms in ISO 17772-2 and ISO 18523-1.

Occupancy					
	Standard	Schedule	Sensible Gain [W/p]	Latent Gain [W/p]	Density Factor [m^2/p]
void	both	/	/	/	/
technical room	both	/	/	/	/
storage room	both	/	/	/	/
heated corridor	ISO 18523	constant, 8/21, max = 1	49	23	20
	ISO 17772	constant, 8/17, max = 1	49	23	20
unheated corridor	ISO 18523	constant, 8/21, max = 1	49	23	20
	ISO 17772	constant, 8/17, max = 1	49	23	20
computer room/laboratory	ISO 18523	constant, 8/16 max = 1	81	38	2
	ISO 17772	constant, 8/16 max = 1	81	38	2
meeting room	ISO 18523	constant, 9/18 max = 1	67.67	31.67	3.3
	ISO 17772	variable, 8/12–13/17 max = 0.9	80.2	38.2	2
office room	ISO 18523	variable, 8/12, max = 1	81	38	10
	ISO 17772	variable, 8/12–13/17	80	38	10
lecture room	ISO 18523	variable, 8/18, max = 1	81	38	2
	ISO 17772	variable, 8/17, max = 0.7	74.52	42.66	5.4

Table A4. Occupancy-based loads for the building rooms in ISO 17772-2 and ISO 18523-1.

Occupancy-Based Load					
	Standard	Appliances		Lighting	Ventilation
		Sensible	Latent [W/m^2]	Sensible [W/m^2]	l/(s·m^2)
void	both	/	/	/	/
technical room	both	300 W *	/	/	/

Table A4. *Cont.*

	Occupancy-Based Load				
	Standard	**Appliances**		**Lighting**	**Ventilation**
		Sensible	**Latent [W/m^2]**	**Sensible [W/m^2]**	**l/(s·m^2)**
storage room	both	/	/	/	/
heated corridor	ISO 18523	/	/	15	0.69
	ISO 17772	/	/	2.44	0.69
unheated corridor	ISO 18523	/	/	15	0.69
	ISO 17772	/	/	2.44	0.69
computer room/laboratory	ISO 18523	40.5 W/m^2	19	20	3.47
	ISO 17772	40.5 W/m^2	19	6.1	4.47
meeting room	ISO 18523	2 W/m^2	0	10	3.33
	ISO 17772	12 W/m^2	0	10	3.8
office room	ISO 18523	12 W/m^2	0	12	1.39
	ISO 17772	12 W/m^2	0	6.01	1
lecture room	ISO 18523	2 W/m^2	0	20	2.78
	ISO 17772	8 W/m^2	0	6.1	3.8

* The value for technical room appliances sensible load is related to the real technical systems in the room.

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