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RESEARCH ARTICLE

Mitigating fit-out waste in rentable offices: The role of flexible design strategies

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Abstract

Fit-out waste generated during building refurbishments has significant environmental consequences, accounting for substantial portions of construction and demolition waste. Over a 50-year lifespan, the total waste generated by a rentable office was found to be approximately four times higher than that of a standard office, while implementing open-plan layouts and movable partitions reduced embodied energy by up to 61.3% and embodied energy loss by 84.3%, respectively.This study investigates the effectiveness of flexible interior strategies—open-plan layouts and movable partition systems—in mitigating the environmental impacts associated with fit-out waste in rentable offices. The analysis, structured around three hypotheses and four office typologies, covers the production, replacement, and refurbishment stages of the building life cycle and evaluates total waste, life cycle embodied energy (LCEE), and embodied carbon (EC).The findings highlight that flexibility-oriented design strategies can significantly reduce material turnover and resource inefficiency in the building sector. However, strategies such as recycling, reuse, and the economic aspects of the interventions are excluded from the scope of this study.

1. Introduction

The emergence of high-rise office buildings can be traced back to the post-Industrial Revolution era, when the accumulation of capital and increasing urban employment created a demand for new typologies of office space. The earliest examples of high-rise offices appeared in the late 19th century, particularly in the urban centers of New York and Chicago, where land scarcity and population density necessitated vertical construction [1]. Throughout the 20th century, as high-rise buildings proliferated, design strategies prioritizing daylight access, open-plan layouts, high ceilings, and compact service cores were adopted to enhance rentability [2].

In the contemporary era, high-rise offices are widely categorized under terms such as ‘flexible office’ [3] and ‘rental office’ [4], reflecting changing work styles and user expectations. These buildings now dominate the skylines of metropolitan cities. According to a recent study of 54 high-rise buildings in Istanbul, Ankara, and Izmir, approximately 24% of them function as office spaces [5].

Notably, in rental buildings, spatial modifications may occur not only during occupancy but also in the pre-occupancy phase.

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These interventions often generate considerable volumes of construction and demolition (C&D) waste and accelerate material consumption [6, 7]. C&D waste results from construction, renovation, and demolition phases and accounts for 10–30% of global landfill waste [8, 9]. Within this category, fit-out waste—originating from tenant-specific interior alterations—constitutes 10–20% of C&D waste and has disproportionately high embodied environmental impacts [10, 11]. In this context, the life cycle of rental offices exerts considerable pressure on ecological systems, contributing to air, water, and soil pollution, and exacerbating climate change [12].

A Swedish study reported that refurbishment-related waste in office spaces amounts to 31–38 kg/m², with an associated embodied carbon footprint of 93–96 kg CO_2e/m^2 [13]. Likewise, Eberhardt et al. [14] found that building materials in long-lifespan office buildings (80+ years) were responsible for 72% of total greenhouse gas emissions and 50% of primary energy use. During tenant transitions, walls and ceilings account for over 70% of the generated waste [15], and material production was identified as the leading contributor to embodied carbon, surpassing impacts from construction or end-of-life phases [16].

Addressing waste at its source has gained momentum in sustainable construction discourse. The waste management hierarchy emphasizes reduction, reuse, and recycling, with minimization regarded as the most effective strategy [17, 18]. Researchers argue that minimizing waste during the design stage is crucial to reducing life-cycle emissions [9].

Flexible building design has been proposed as a viable strategy, allowing spatial adaptability without demolition and thereby reducing material turnover and fit-out waste. Li & Yang [19] emphasized the need for innovative design strategies for waste reduction in office interiors. Forsythe and Fini [20] quantified that up to 55% of fit-out waste in Australian office refurbishment projects ends up in landfills, primarily due to rigid space planning and materials that are difficult to disassemble.

Salgın et al. [6], in a study on a multifunctional public building in Kayseri, demonstrated the value of maximizing vertical and horizontal openings to allow different spatial uses over time. Similarly, Mateus et al. [21] found that movable partitions enhance both flexibility and sustainability by minimizing waste generation. Modular components such as raised floors, suspended ceilings, and demountable panels are seen as essential features of adaptable office interiors [22, 23].

Although the environmental implications of tenant changes have been examined in terms of waste quantification [20], life-cycle cost assessment [24], and flexible interior systems [14], few studies have addressed the embodied energy and carbon impacts of such transformations, particularly in the context of megacities. Moreover, the environmental impact of interior flexibility have rarely been quantified through life cycle assessment (LCA) methods. To address this research gap, the present study evaluates how flexible interior strategies in rentable offices can mitigate fit-out waste, embodied energy (EE), and embodied carbon (EC). “Embodied energy loss” is also introduced to highlight the resource inefficiencies associated with premature removal of building components. As waste prevention is the primary step in the waste management hierarchy, this study contributes to the environmental sustainability agenda of urban office design. This study was conducted to guide designers, office owners, and material manufacturers toward more durable and resource-efficient building applications. While the scope of this study focuses on environmental indicators such as embodied energy, carbon emissions, and waste production, the results may also form a basis for future research integrating the economic and investment aspects of sustainable office design. Economic aspects, reuse and recycling strategies are excluded from the scope of this study.

2. Material and Methodology

This section outlines the materials and methodological framework employed in the study. The methodology is structured around the testing of three core hypotheses concerning the environmental implications of flexible interior design strategies in rentable office buildings.

2.1. Objective, assumptions, and delimitations

The primary objective of the study is to evaluate how flexible design strategies—specifically open-plan layouts and movable partition walls—affect environmental outcomes in rentable offices. The analysis focuses on four office types located in Ankara, Türkiye's capital city, assessing parameters such as waste generation, total embodied energy (LCEE), energy losses, and global warming potential (GWP) across the building life cycle.

Three hypotheses were formulated and tested across four office typologies. In defining these hypotheses, multiple user and material change scenarios were established. The study is limited to the GWP category; other environmental impact indicators (e.g., acidification, eutrophication), strategies such as recycling, reuse and economic aspect of the strategies are excluded from scope.

The study examines four office configurations to evaluate the influence of flexibility strategies on material consumption and environmental impact:

Office 01: S – Standard office with a closed-plan layout and fixed partitions (no tenant change assumed)

Office 02: RCF – Rentable office with closed-plan layout and fixed partitions

Office 03: ROF – Rentable office with open-plan layout and fixed partitions

Office 04: RCM – Rentable office with closed-plan layout and movable partitions

In the standard office, material replacement occurs only upon reaching the end of service life (B4 phase), whereas in rentable types, material changes are triggered by tenant transitions.

The assumed service life of the office unit is 50 years, consistent with similar studies [14, 25]. Lease duration is defined as five years, based on real estate consultant interviews and literature, indicating typical tenant turnover for office spaces under 1000 m² [10]. It is assumed that the initial tenant is a non-health-related business, followed by a health sector occupant—triggering interior modifications—repeating every five years. Two sensitivity analyses were conducted to determine the influence of these parameters.

Interior wall material, floor and ceiling coverings were considered as having the largest area and are the most frequently replaced materials. The building materials of the offices were selected as carpet tiles and linoleum on the floor, gypsum panels and glass on the walls, paint for open ceilings and gypsum panels for suspended ceilings to match the types of companies. Paint and rock wool applied with gypsum board/panel also taken into consideration. In addition, a movable partition wall made of medium density board (MDF) was applied as a separate scenario for both health-related and non-health-related office types.

Material properties (density, unit mass, service life, unit embodied energy) were collected from Environmental Product Declarations (EPDs). The One Click LCA software was employed to calculate GWP using EN 15978 methodology [26]. This platform is widely used in LCA-based research in the building sector due to its comprehensive material database [27, 28].

Environmental impacts were evaluated over the life cycle stages A1–A3 (production), B4 (replacement), and B5 (refurbishment). Following Moisio et al. [29], B4 encompasses replacements due to end-of-life; B5 covers changes due to user needs (e.g., tenant changes). Obrecht et al. [30] emphasize the importance of distinguishing between these cycles in environmental assessments.

Three hypotheses were tested:

- Hyp. A: Rentable offices generate greater amounts of fit-out waste (kg/m²) and higher life-cycle embodied energy (LCEE, MJ/m²) than standard offices.
- Hyp. B: Among rentable offices, those with closed-plan configurations produce more fit-out waste (kg/m²) and exhibit higher LCEE (MJ/m²) than open-plan equivalents.
- Hyp. C: Incorporating movable partitions instead of fixed ones in rentable offices reduces total fit-out waste generation (kg/m²) and improves LCEE (MJ/m²) performance.

These hypotheses were tested through a comparative LCA of four office typologies, where fit-out waste, LCEE, and EC were used as the main quantitative indicators. These indicators were examined by modeling four office types in Autodesk Revit, extracting material quantities through BIM schedules, and computing environmental data via One Click LCA. Material and occupancy scenarios were based on real estate data and tenant change patterns. A summary of the office typologies, service life, replacement cycles, simulation tools, databases, and core research themes is presented in Fig. 1.

To provide a clear overview of the research workflow, Fig. 1 summarizes the methodological steps followed in this study. Step 1 presents the selection of the case building and the context. Step 2 outlines the formulation of hypotheses and their relationship with office types. Step 3 illustrates the BIM-based modeling and data collection process. Step 4 shows the evaluation of the scenarios using One Click LCA and Excel. Finally, Step 5 presents the comparative analysis the results. These five stages collectively represent the methodological framework applied throughout the study.

2.2. Case study

The case study was selected based on representativeness and accessibility criteria. Ankara, the capital of Turkey, was chosen because it is a metropolis with a high concentration of office buildings and high-rise commercial structures, reflecting the country's contemporary building practices. The selected high-rise office building represents the modern office structures commonly found in metropolitan areas, featuring a central core and flexible office units suitable for various usage models. Further reasons for selecting the building include the availability of accessible data and architectural plans that facilitate embodied energy analysis. The building comprises 18 floors, each containing four separate office units measuring 234 m².

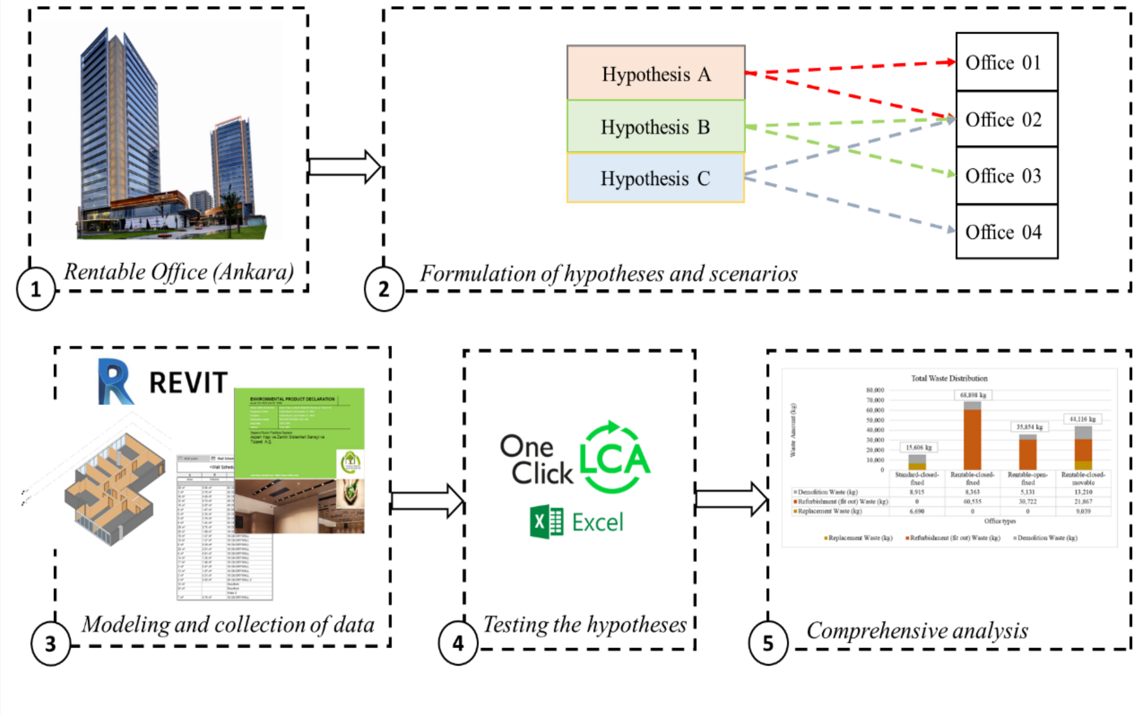


Fig. 1. Workflow of the study

For the purposes of this study, a single office unit was analyzed. The layout of the selected unit includes an entrance, six enclosed offices, a kitchen, a meeting room, and two restrooms. To develop an alternative office type based on spatial flexibility, an open-plan layout was also modeled by merging the individual office spaces with the entrance area (Fig. 2).

To obtain detailed and up-to-date information on rentable office practices, a semi-structured interview was conducted with the building's sales consultant. The interview aimed to gather qualitative data related to tenant behaviors, interior material choices, and the building's functional configuration. The key findings obtained from the interview, which form the empirical basis of this study, are summarized below:

- The average lease renewal or tenant turnover cycle is approximately every five years.
- Tenants generally belong to either the healthcare or non-healthcare sectors.
- Standard material finishes currently in use include:
    - ✧ Carpet tiles for flooring
    - ✧ Drywall for partition walls
    - ✧ Paint applied directly to open ceilings
- For tenants in the healthcare sector, alternative materials are often preferred for functional and hygienic reasons. These include linoleum flooring, glass partition walls, and plasterboard ceilings to facilitate natural lighting and maintain sanitary conditions.

2.3. Embodied energy and embodied carbon

Embodied energy (EE) refers to the total energy consumed throughout the life cycle of building materials, including their production, transportation, installation, maintenance, replacement, and eventual demolition [31]. Embodied carbon (EC), on the other hand, represents the amount of greenhouse gas emissions associated with these processes [32]. Both EE and EC are calculated by multiplying the unit value of a material (MJ/kg for EE or $kgCO_2e/kg$ for EC) by the material's total mass (kg).

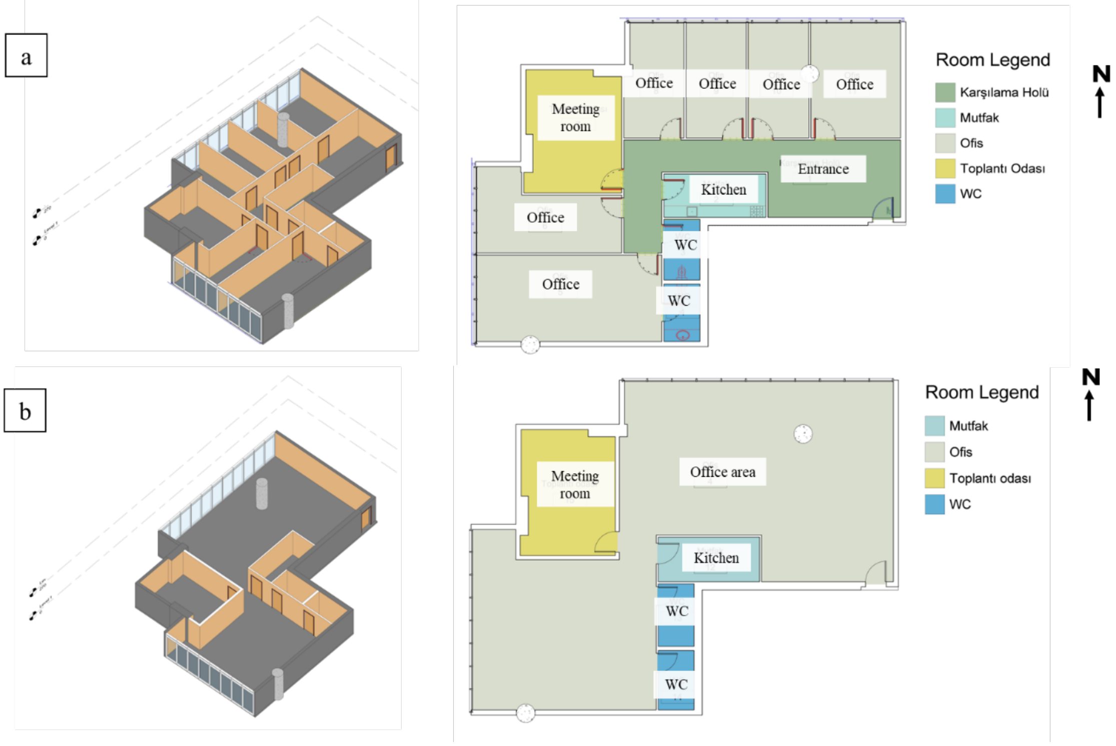


Fig. 2. The office unit with closed-plan (standard office) (a) and open-plan (b)

This study evaluates the lifecycle embodied energy (LCEE) and embodied carbon (EC) of an office unit over a 50-year service period. Calculations were performed manually using Microsoft Excel. The manual calculation method was selected because the Environmental Product Declarations (EPDs) for the analyzed materials were obtained directly from the manufacturers. Each EPD provides standardized environmental impact indicators per functional unit (e.g., 1 kg or 1 m²). No LCA software was used in the study because it was not deemed necessary to re-enter the standardized values already available in the EPDs into a database. Since the scope of the study focused solely on the embodied carbon calculation (A1-A3, B4-B5 phases) of specific materials, there was no need for the modules of a comprehensive process-based LCA software. Manual calculations were obtained directly from EPD data in accordance with international standards (EN 15804 and ISO 14044).

The selection of building materials is based on the type of tenant sector—healthcare or non-healthcare. As detailed in Table 1, offices occupied by companies outside the health sector use gypsum board (including rock wool insulation and paint) for interior walls, carpet for flooring, and painted open ceilings. In contrast, healthcare offices use glass partition walls, linoleum flooring, and suspended gypsum panel ceilings to meet hygiene and lighting needs. Paint is assumed to be renewed with each tenant change, regardless of sector.

Service lives for materials exceeding 20 years in Environmental Product Declarations (EPDs) are standardized as 25 years to match evenly with the 50-year service life of the building. While most interior materials are assumed to be replaced at every tenant change (i.e., every 5 years), movable partition walls are assigned a replacement cycle of 25 years due to their reusability and spatial adaptability.

Both renewable and non-renewable resource consumption is included in the calculations. Building materials were selected based on proximity to the case study location and the availability of reliable EPDs from manufacturers (Table 2). For the movable and glass partition walls, material specifications were obtained through direct communication with a representative from Aspen.

This study introduces a concept termed “Embodied Energy Loss” (EEloss), which quantifies the energy wasted due to the disposal of a building material prior to the end of its expected service life. EEloss serves as an indicator of inefficiency in material utilization, particularly relevant in rentable office buildings where frequent interior refurbishments are common.

Table 1. Office types, plan layout and building materials

Office type	Company type	Plan scheme	Partition type	Floor	Wall	Ceiling	Frequency of tenant change
Standard	Non-health	Closed	Fixed	Carpet	Gypsum board	Paint	-
Rentable	Non-health	Closed	Fixed	Carpet	Gypsum board	Paint	5 years
Rentable	Health	Closed	Fixed	Linoleum	Glass	Gypsum board	5 years
Rentable	Non-health	Open	Fixed	Carpet	Gypsum board	Paint	5 years
Rentable	Health	Open	Fixed	Linoleum	Glass	Gypsum board	5 years
Rentable	Non-health	Closed	Movable	Carpet	MDF system	Paint	5 years
Rentable	Health	Closed	Movable	Linoleum	MDF system	Gypsum board	5 years

Table 2. Database of the selected building materials

Material	EE (MJ/kg)	EC (kgCO2e) (A1-A3)	Source
Gypsum board	4.2	1.72	[33]
Rock wool	32.12	19.6	[34]
Paint	25.7	1.72	[35]
Glass panel	75.2	115	Personel communication
MDF panel	50.2	73.2	Personel communication
Carpet tile	36.9	5.03	[36]
Linoleum	54.4	6.51	[37]

In the scope of this research, it is assumed that all waste is directed to landfills at the end-of-life stage. Therefore, tracking EEloss provides valuable insight into energy losses embedded in materials that are prematurely removed and discarded.

$$EE_{loss} = EE_m - [EE_m * (t_p / t_s)] * t \quad (1)$$

where:

EE_{loss} is the embodied energy loss (MJ),

EEm is the embodied energy required for manufacturing the material (MJ),

t_p is the actual time the material is used in the building (years),

t_s is the nominal service life of the material (years).

t represents the number of times the material is replaced or used over the building's 50-year lifecycle.

By incorporating EE_{loss} into the assessment, this study emphasizes the importance of material longevity and design strategies that reduce premature replacement, thereby supporting more sustainable construction practices.

2.4. Office utilization and material change scenarios

Tenant turnover in rentable office spaces typically results in the replacement of interior finishes—particularly wall partitions, flooring, and ceiling materials—leading to significant amounts of fit-out waste. In this study, it is assumed that each tenant occupies the office for a 5-year period, with alternating tenant types representing non-health-related sectors (e.g., software, architecture, law) and health-related sectors (e.g., medicine, chemistry, sports).

This tenant alternation cycle continues over the 50-year service life of the office unit, with interior materials being replaced at the end of each lease period. These recurring modifications simulate real-world refurbishment patterns that contribute to embodied energy losses and carbon emissions. The material change scenarios for each office type over the service life are detailed in Table 3, illustrating how different interior layouts and material strategies affect overall environmental performance.

Additionally, the waste generated throughout the life cycle of the office units was categorized under three main stages: refurbishment, replacement, and demolition. Waste resulting from the scheduled replacement of materials that have reached the end of their designated service life is classified under Stage B4 (Replacement). In contrast, premature removal of materials due to tenant changes—before the materials reach their end-of-life—is classified under Stage B5 (Refurbishment).

Based on the material usage sequence outlined in Table 3, materials installed by the final tenant and remaining in place at the end of the 50-year service life of the office unit are considered demolition waste, and are accounted for under Stage C1 (End-of-Life), as summarized in Table 4.

2.5. Effect of parameter variations on results

Due to the variability of input parameters, reliance on assumptions, and incomplete information, it is important to identify uncertainties through sensitivity analysis in LCA [38].

Table 3. Scenarios for material changes during the service life of the office

Years	Wall	Floor	Ceiling
1-5	Gypsum board	Carpet tile	Paint
6-10	Glass panel	Linoleum	Gypsum board
11-15	Gypsum board	Carpet tile	Paint
16-20	Glass panel	Linoleum	Gypsum board
21-25	Gypsum board	Carpet tile	Paint
26-30	Glass panel	Linoleum	Gypsum board
31-35	Gypsum board	Carpet tile	Paint
36-40	Glass panel	Linoleum	Gypsum board
41-45	Gypsum board	Carpet tile	Paint
46-50	Glass panel	Linoleum	Gypsum board

Table 4. Service life and frequency of change of building materials due to office type

Material	Service life	Replacement (B4) cycle	Refurbishment (B5) cycle
G. board	50	0	4 (rentable)
R. wool	50	0	4 (rentable)
Glass	25	0	4 (rentable)
Carpet	10	4 (standard)	4 (rentable)
Linoleum	25	0	4 (rentable)
Paint	5	9 (standard)	4 (rentable)
M.partition	25	1 (rentable)	0

*(G.board: gypsum board; R.wool: rockwool; M.partition: movable partition)

To assess the robustness of the results, a deterministic one-at-a-time (OAT) sensitivity analysis was performed by varying two key parameters (tenant turnover rate and building service life) by ±20% from its base value. The reason for selecting a ±20% variation range is that this is a standard value often accepted as the margin of uncertainty in material properties or model parameters [39]. The environmental impacts include total waste generation and embodied energy over the building's lifetime.

2.6. Data adjustment for benchmark comparison

To validate the findings, the waste quantities calculated in this study were compared with existing benchmarks in the literature. Since previous studies present waste amounts on a per square meter basis for single refurbishment events, the current results were normalized accordingly. The study assumes a 50-year service life for each office unit, with nine refurbishment cases and one demolition over this period. Accordingly, one-time refurbishment waste has been calculated using the following equation to make it comparable with other studies.

$$O_W = {}^{T_W}\!/_{n} \tag{2}$$

where:

O_w indicates waste amount per one-time refurbishment (kg/m²); Tw represents total refurbishment waste amount over 50 years (kg/m²); and n is the number of refurbishment cycles in 50 years. n is taken as 9.

3. Results and Discussion

This section presents the outcomes of the hypothesis testing outlined previously. The validity of Hypotheses A, B, and C is evaluated in sequence, followed by an analysis of the embodied environmental impacts of the applied flexible design strategies.

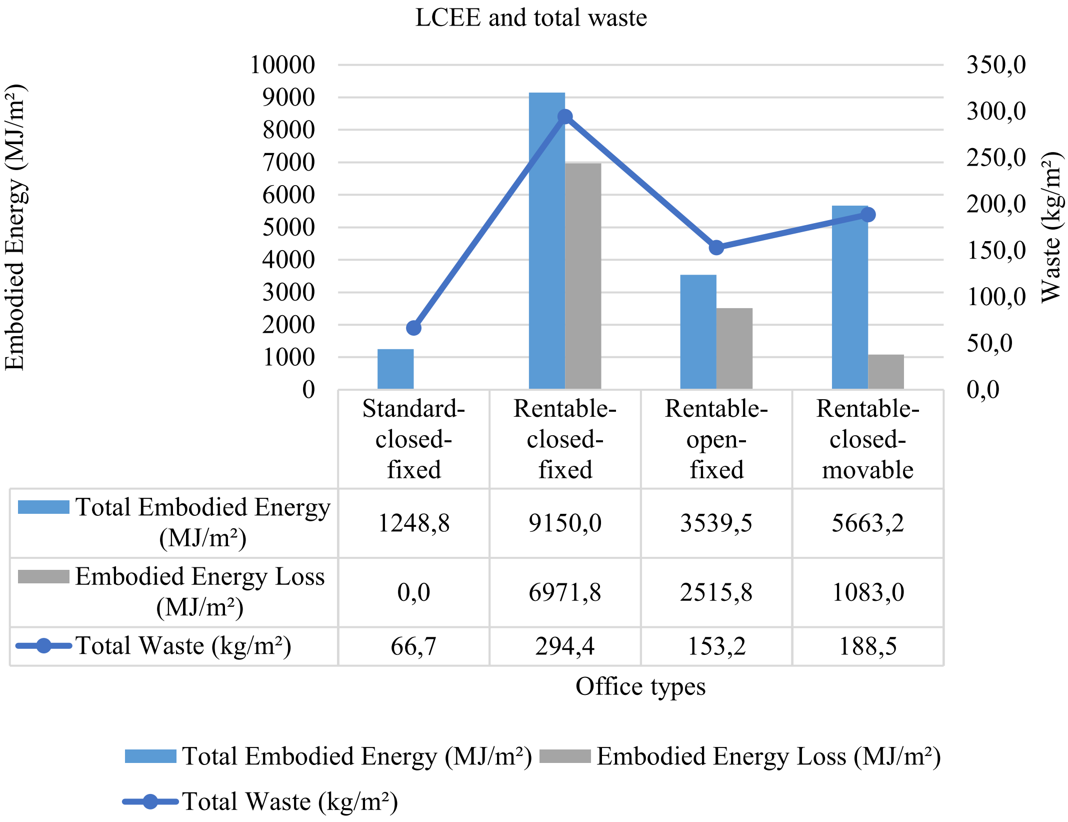
3.1. Hypothesis testing

Hypothesis A compares LCEE (MJ/m²) and total waste generation (kg/m²) of a standard office and a rentable office with a closed-plan layout and fixed partitions across life cycle stages A1–A3, B4, and B5. The findings reveal that the rentable office has a 7.3-fold increase in LCEE and a 4.4-fold increase in total waste compared to the standard office. Because all material service lives are multiples of the building's 50-year service life (5, 10, 25 years), the standard office incurs no EE loss, whereas the rentable office incurs more EE loss due to premature material replacements. Given that both LCEE and waste generation are lower in the standard office, Hypothesis A is validated.

To test Hypothesis B, two rentable office types with fixed partitions—one with a closed-plan and the other with an open-plan scheme—were compared. Results show that the open-plan layout reduces LCEE by 61.3%, EE loss by 64%, and total waste by 48% relative to the closed-plan layout. These findings confirm the validity of Hypothesis B.

Hypothesis C was evaluated by comparing rentable offices with closed plans utilizing either fixed or movable partitions. The use of movable partitions reduced LCEE by 38.1%, EE loss by 84.3%, and total waste by approximately 36% compared to fixed partitions. Thus, Hypothesis C is supported.

Overall, the open-plan layout proves to be most effective in minimizing total waste, whereas movable partitions are more efficient in reducing embodied energy loss (Fig. 3). In terms of overall life cycle embodied energy (LCEE) performance, the ranking from most to least favorable scenario for rentable offices is open-plan layout with fixed partitions, closed plan with movable partitions and closed-plan with fixed partitions.



	Standard-closed-fixed	Rentable-closed-fixed	Rentable-open-fixed	Rentable-closed-movable
Total Embodied Energy (MJ/m²)	1248,8	9150,0	3539,5	5663,2
Embodied Energy Loss (MJ/m²)	0,0	6971,8	2515,8	1083,0
Total Waste (kg/m²)	66,7	294,4	153,2	188,5

Fig. 3. Comparison of four office types in terms of total embodied energy, embodied energy loss and total waste

When examining the life cycle stages of the office types individually, it becomes evident that rentable offices consume more than five times the embodied energy of standard offices during the production phase (A1–A3). This is primarily due to the frequent use of varied materials, with each material's first application being assessed within the production scope. However, implementing an open-plan layout in rentable offices reduces the embodied energy consumed during this phase by approximately 61%. Conversely, the introduction of movable partitions increases the embodied energy in the production phase.

In the replacement phase (B4), no embodied energy was recorded for the standard or rentable offices with fixed partitions. This is because materials in rentable offices are seldom used for their overall service life due to tenant changes every five years. However, in rentable offices with movable panels, the embodied energy associated with replacements is approximately twice as high as in standard offices, owing to the continued material changes throughout the building's lifecycle.

Tenant turnover also necessitates the introduction of new materials, particularly during the refurbishment phase (B5). Fig. 4 illustrates the EE comparison between different stages. In this comparison, the total embodied energy (EE) of each scenario is normalized to 100%, and the contribution of each lifecycle stage (A1–A3 Product, B4 Replacement, and B5 Refurbishment) is presented as a percentage of the total. The most remarkable improvement is observed in the rentable-closed-movable case. Thus, the comparison reveals that employing movable partition systems can effectively redistribute and reduce embodied energy demand across the building life cycle (Fig. 4).

3.2. Total waste distribution

A detailed assessment of total waste generation reveals that rentable offices produce four times more waste than standard offices, even when both share identical plan schemes and fixed partition walls. This increase is solely attributed to tenant turnover, which leads to frequent interior alterations. In contrast, demolition waste levels are comparable between the two office types.

When the plan scheme of the rentable office is modified to an open-plan layout, the total waste amount is reduced by 48%, primarily due to a 50% decrease in fit-out waste. Additionally, open-plan configurations lead to lower end-of-life waste compared to closed-plan schemes, reflecting their more efficient material use.

The integration of movable partition walls further reduces the total waste by approximately 36% compared to fixed partition walls. This is because movable partitions provide spatial flexibility and are retained for longer periods despite frequent tenant changes. Notably, fit-out waste is lowest in the office type employing movable partitions among all rentable office models.

However, replacement and demolition waste are slightly higher in these configurations. This is explained by the completion of the movable partition’s service life, which necessitates a one-time replacement during the office's 50-year life span (Fig. 5).

3.3. Embodied carbon

Embodied carbon across the different life cycle stages of each office typology were calculated using the One Click LCA tool, following the EN 15978 methodology. Results indicate that adopting an open-plan layout has the most significant effect in reducing greenhouse gas emissions, particularly during the production stage (A1–A3).

By contrast, the highest emissions from material exchange activities (stages B4–B5) were observed in the rentable office with a closed plan scheme and fixed partitions, where frequent tenant turnover necessitates repeated material replacement and refurbishment.

Overall, the implementation of an open-plan configuration in rentable offices results in a 61% reduction in total embodied carbon emissions. Similarly, the use of movable partition systems contributes to a 45.2% reduction in total global warming potential (GWP) when compared to standard fixed-partition office layouts (Fig. 6).

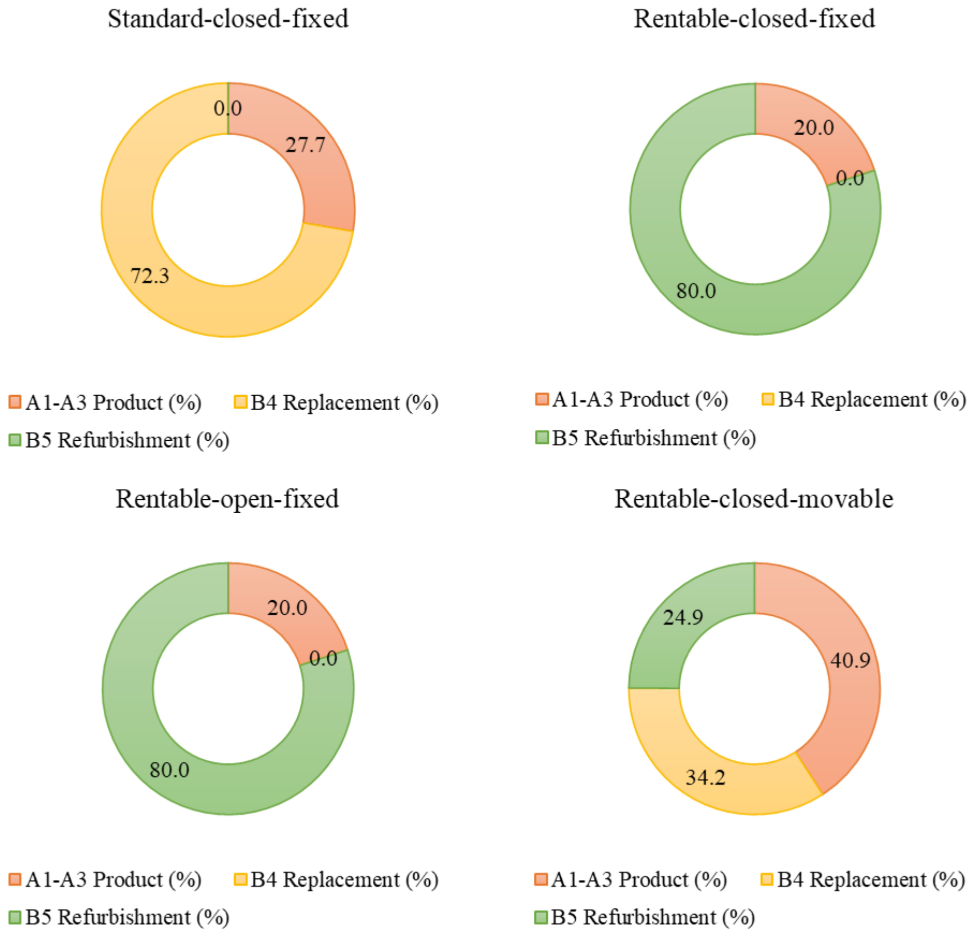


Fig. 4. Comparison of embodied energy of the lifecycle stages (%)

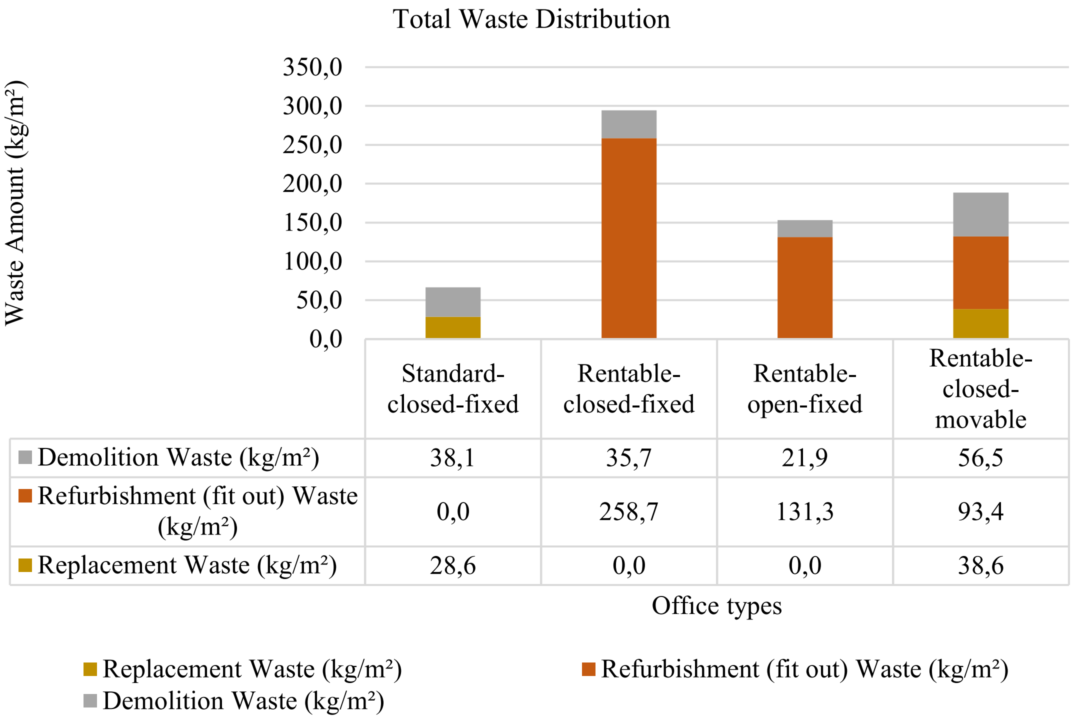
These findings demonstrate that spatial flexibility strategies—specifically open-plan design and movable partitions—not only minimize material waste but also substantially mitigate embodied carbon emissions over the building's lifecycle.

3.4. Building components and materials

A more granular evaluation of the embodied environmental impacts associated with specific building components and materials provides critical insight into the sustainability performance of different office configurations. To this end, the study analyzes the types of waste, total embodied energy (EE), and embodied energy losses (EE_{loss}) generated by material changes over a 50-year lifecycle of the rentable office typologies.

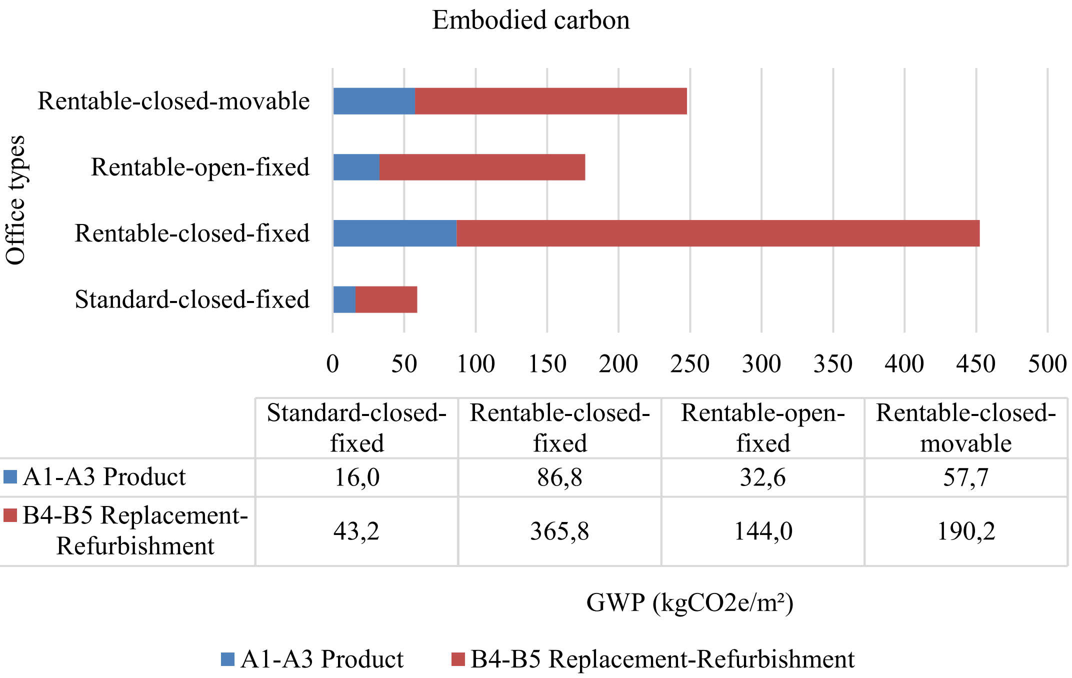
For ceilings, the analysis includes gypsum board, rock wool, and paint in the case of suspended systems, and only paint for open ceiling configurations. Carpet tiles and linoleum are considered for flooring, while wall assemblies incorporate gypsum panels, glass partitions, rock wool, paint, and movable medium-density fiberboard (MDF) partitions, depending on the office type and function.

Among these, the flooring contributes the least to both material waste and embodied energy, owing to its limited material diversity. In contrast, ceilings exhibit the lowest lifecycle embodied energy (LCEE) due to the relatively low energy intensity of gypsum board and minor quantities of paint and insulation.



	Standard-closed-fixed	Rentable-closed-fixed	Rentable-open-fixed	Rentable-closed-movable
■ Demolition Waste (kg/m²)	38,1	35,7	21,9	56,5
■ Refurbishment (fit out) Waste (kg/m²)	0,0	258,7	131,3	93,4
■ Replacement Waste (kg/m²)	28,6	0,0	0,0	38,6

Fig. 5. Waste generation due to plan layout and partition type



	Standard-closed-fixed	Rentable-closed-fixed	Rentable-open-fixed	Rentable-closed-movable
■ A1-A3 Product	16,0	86,8	32,6	57,7
■ B4-B5 Replacement-Refurbishment	43,2	365,8	144,0	190,2

Fig. 6. Comparison of embodied carbon of the lifecycle stages ($kgCO_2e/m^2$)

For all rentable office scenarios, the embodied energy and waste associated with floor and ceiling components remain constant: approximately 1289 MJ/m² and 30 kg/m² for flooring, and 584 MJ/m² and 82 kg/m² for ceilings, respectively.

The walls, however, display substantial variation across scenarios, primarily because wall components are directly affected by the plan layout and partitioning strategy. Walls represent the dominant source of material waste, largely due to their expansive surface area and higher turnover rates. For instance, in the rentable office with a closed plan and fixed partitions, wall-related waste reaches 183 kg/m², while this figure is significantly reduced in the open-plan scenario (42 kg/m²) and the movable partition scenario (77 kg/m²).

In terms of embodied energy loss, walls again constitute the most significant contributor. The closed-plan, fixed-partition office exhibits the highest EEloss at 5779 MJ/m², while the movable partition scenario eliminates EE losses entirely (0 MJ/m²), as the panels are reused throughout the building's life without premature removal (Fig. 7).

These results reinforce the importance of flexibility in wall systems—particularly the use of demountable partitions—in minimizing both material waste and energy losses, thereby supporting environmental sustainability goals in office design and refurbishment practices.

3.5. Material-based embodied energy and waste analysis

Building materials are among the primary determinants of embodied energy (EE) demand in buildings. In addition to their unit EE intensities and physical quantities, other critical factors such as replacement/refurbishment frequency and material service life substantially influence the lifecycle embodied energy (LCEE). To evaluate these effects, key interior materials—gypsum board, rock wool, paint, glass panels, carpet tiles, linoleum, and medium-density fiberboard (MDF) used for movable partitions—were compared across rentable office types in terms of both waste generation and embodied environmental impact.

As the flooring system remains constant across all office configurations, carpet tiles and linoleum perform identically in each scenario and are therefore represented only once in Fig. 6. In contrast, materials used in interior wall assemblies (gypsum board, rock wool, paint, and glass) are highly influenced by flexible design strategies, particularly those involving layout and partition modifications.

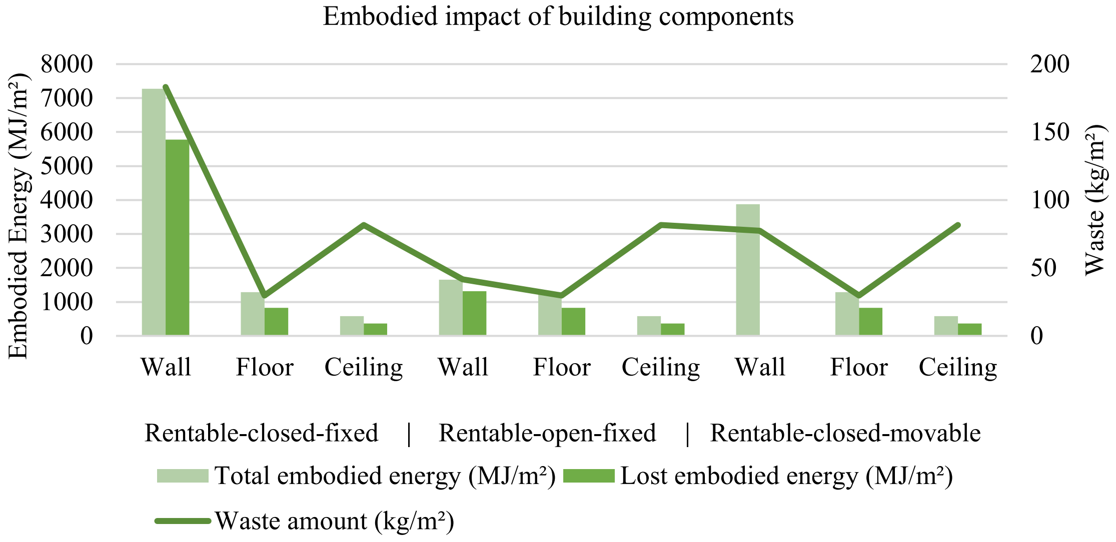


Fig. 7. Embodied energy and waste amount of building components for rentable offices

In rentable offices with movable partitions (RCM), only MDF is utilized for wall divisions, whereas gypsum board, rock wool, and paint are still present in ceiling components and thus retained in the analysis. Performance comparisons are organized by office type: rentable–closed plan with fixed partitions (RCF), rentable–open plan with fixed partitions (ROF), and rentable–closed plan with movable partitions (RCM).

Among all materials, glass panels exhibit the highest LCEE, reaching 6736 MJ/m² in RCF, followed by MDF at 3878 MJ/m². This is primarily due to their high EE intensities: glass at 75.2 MJ/kg and MDF at 50.2 MJ/kg. Although linoleum also has a high unit EE (54.4 MJ/kg), its relatively low quantity results in a modest overall LCEE. Notably, paint and MDF showed zero EE loss, attributed to the synchronization of their service lives with the 50-year building lifespan, eliminating premature material disposal.

In terms of waste generation, results further confirm that flexible design strategies contribute to material conservation. Over the building's life cycle, gypsum board waste decreased from 158.7 kg/m² in RCF to 91.3 kg/m² in ROF, and further to 71.3 kg/m² in RCM. Rock wool waste showed a similar trend: 5.5 kg/m² in RCF, 3.9 kg/m² in ROF, and 3.4 kg/m² in RCM. For glass panels, waste was significant in fixed-wall offices—approximately 89.6 kg/m² in RCF—but dropped to 20.5 kg/m² in ROF, reflecting reduced material usage due to open-plan configurations (Fig. 8).

These findings emphasize that adopting flexible spatial configurations, particularly movable partitions and open-plan layouts, can play a critical role in minimizing both material waste and embodied energy across the building life cycle.

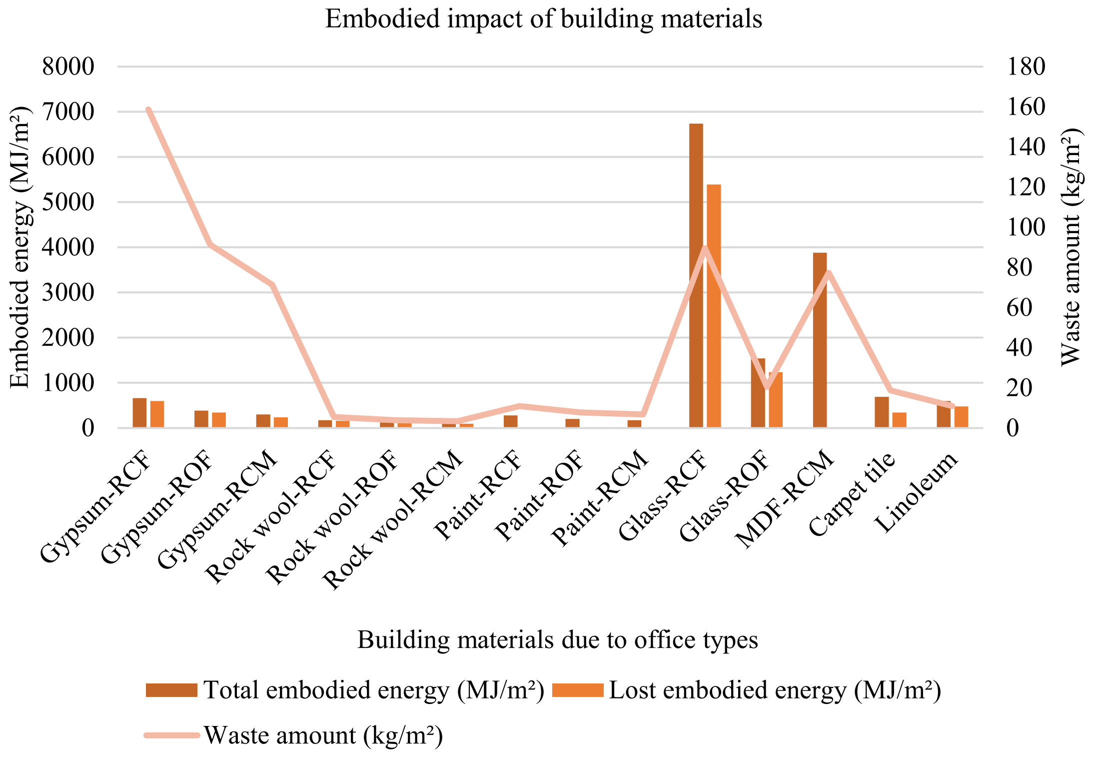


Fig. 8. Embodied energy (MJ/m²) and waste amount (kg/m²) of building materials for rentable offices

3.6. Sensitivity analysis

The sensitivity analysis shows that the tenant turnover rate has a significant impact on both total material waste and life cycle embodied energy (LCEE). For instance, increasing the tenant turnover rate by 20% leads to an increase of up to 32.9% in total waste and up to 23.8% in LCEE in the RCF scenario. Conversely, a 20% decrease in the turnover rate reduces waste and LCEE by reasonable amounts. Among the scenarios, the ROF scenario shows the highest sensitivity to tenant turnover; a ±20% change leads to the largest changes in total waste and LCEE, at 34.4% and 27.4%, respectively. The RCM scenario shows relatively lower sensitivity, indicating that design choices such as movable partitions can mitigate the environmental impact of frequent tenant turnover.

±20% changes in building service life had a minimal impact on total waste and LCEE across all scenarios, indicating that the results are relatively insensitive to reasonable assumptions regarding service life (Fig. 9). Overall, these findings emphasize that tenant turnover rate is a critical factor affecting total building material waste and embodied energy, whereas changes in building service life within the range considered have a limited impact. This highlights the importance of flexible interior strategies in managing environmental impacts under changing usage conditions.

To assess the reliability of the parameters, the ranking stability of office types was examined through the variable variation range. Considering that the main objective of the study was to compare office types, it was observed that the results did not change when the office rankings were checked for each scenario. Although uncertainty analysis requires the assignment of probability distributions and the execution of Monte Carlo simulations, the focus of this study was to evaluate the relative impact of the fundamental assumptions that constitute the study. Therefore, sensitivity testing was deemed sufficient at this stage. Probabilistic uncertainty analysis is recommended for future research.

3.7. Comparison with literature values

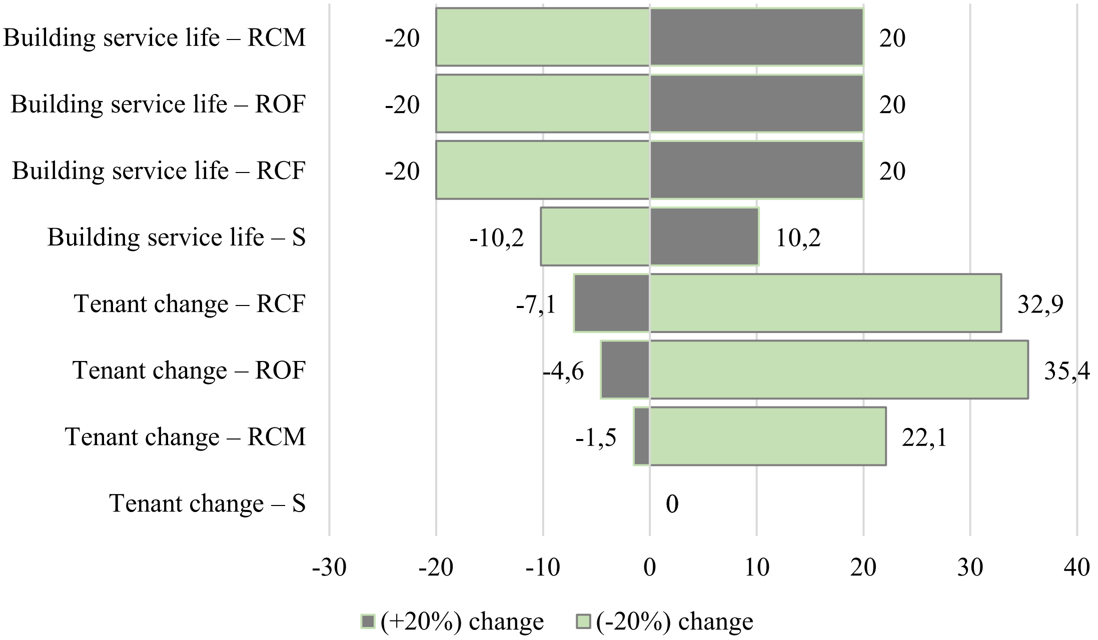
To ensure comparability with literature values, which typically report waste generation from a single refurbishment event ($kg \cdot m^{-2}$ per refurbishment), the model outputs were converted accordingly. In this study, the 50-year total refurbishment waste ($kg \cdot m^{-2}$) was divided by the assumed number of refurbishment cycles (nine times over 50 years, based on the tenant turnover of 5 years). This conversion yielded the waste generated in a single refurbishment cycle, allowing direct comparison with published benchmarks. One-time refurbishment waste occurring in this study was calculated using Equation 2. The results obtained are as follows:

- The rentable-closed-fixed (RCF) office scenario generates 28.7 kg/m^2 of waste per refurbishment cycle.
- The rentable-open-fixed (ROF) scenario results in 14.6 kg/m^2 per cycle.
- The rentable-closed-movable (RCM) alternative yields 10.4 kg/m^2 per cycle.

These figures were then benchmarked against literature values. Budiyani [13] reported waste values for four office refurbishment projects in Sweden, while Forsythe and Fini [20] conducted an extensive study across 23 office fit-out projects in Australia. Only case studies where one floor had been stripped out were considered from the data in the study by Forsythe and Fini. This is to ensure that consistent results are obtained with this study. The ranges of waste generated as a result of one-time refurbishment are given in Table 5.

As shown in Table 5, the estimated renovation waste values in this study are generally consistent with the range of 24–52 $kg \cdot m^{-2}$ [20] and 31–38 $kg \cdot m^{-2}$ [13] reported in previous studies. The rentable-closed-fixed configuration, representing the conventional rentable office layout without flexible design solutions, produced 28.7 $kg \cdot m^{-2}$ of refurbishment waste; this value is within the mid-range of values in the literature. Even if the number of the studies is limited, this consistency supports the reliability of the modeling approach and demonstrates that the study's assumptions are based on empirical findings.

(a) Impact of ±20% variation on total waste



(b) Impact of ±20% variation on LCEE

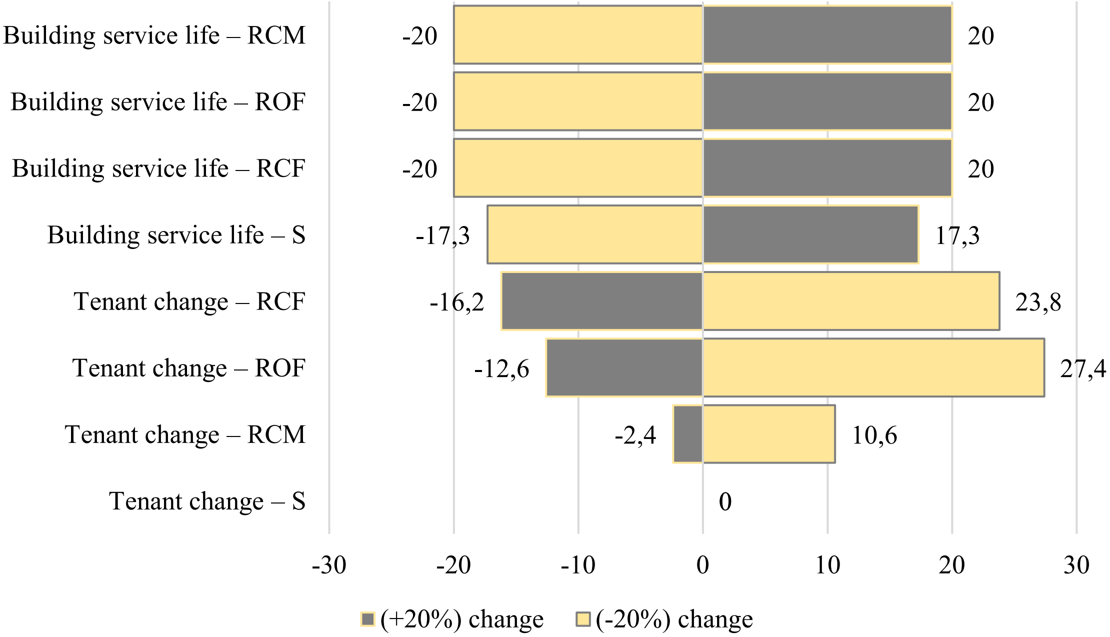


Fig. 9. Sensitivity analysis using the OAT approach (±20% variation) showing the influence of parameters on total waste (a) and total embodied energy (b)

Table 5. Comparison of refurbishment waste with literature findings (temporally normalized per single refurbishment cycle, kg·m⁻²)

Source	Fit-out waste generated in a one-time refurbishment project (kg/m²)
[20]	24.1 – 52.1 kg/ m²
[13]	31-38 kg/m²
Rentable-closed-fixed (this study)	28.7 kg/m²
Rentable-open-fixed (this study)	14.6 kg/m²
Rentable-closed-movable (this study)	10.4 kg/m²

In contrast, layouts incorporating spatial flexibility, such as rentable-open-fixed and rentable-closed-movable types, showed significantly lower waste production (14.6 and 10.4 kg·m⁻², respectively). These reductions can be attributed to the minimization of demolition and material replacement needs through open-plan and modular design strategies. The results confirm that flexible and demountable interior systems can significantly reduce renovation-related waste and are consistent with previous studies emphasizing design for adaptability and reuse.

Overall, the findings indicate that spatial configuration and partition type are decisive factors in concrete resource performance. The close alignment between the rentable-closed-fixed scenario and established reference values enhances the model's reliability, while the lower waste intensities observed in flexible configurations highlight the environmental potential of adaptable design strategies in the rentable office sector. These insights provide strong evidence that integrating flexibility principles into rentable buildings can significantly reduce refurbishment waste and contribute to circular economy goals.

3.8. Limitations of the study

This study presents a series of scenarios based on a selected high-rise office building, focusing on different material types, office configurations, and refurbishment cycles in relation to tenant changes. While these scenarios offer useful insights into the embodied impacts of rentable office configurations, they are shaped by a number of assumptions that inherently limit the generalizability of the findings. Moreover, this study is based on the analysis of a single office building; therefore, the findings cannot be generalized to all office buildings. Variations in building design, occupancy patterns, and refurbishment practices may lead to different outcomes in other contexts.

A primary limitation stems from the scarcity of empirical data and prior research specifically addressing waste generation and embodied impacts in rentable office buildings. Due to this gap, the study’s assumptions—particularly regarding tenant change frequency and refurbishment cycles—were informed by limited literature and stakeholder interviews. Consequently, the comparison of waste quantities is constrained by the small number of relevant studies available, limiting the scope for broader benchmarking.

Additionally, although materials with verified Environmental Product Declarations (EPDs) were selected to ensure data reliability and consistency, it is acknowledged that a wide variety of alternative materials may be used in office fit-outs. This could result in variability in embodied energy (EE) and waste profiles not captured within the selected material set. Moreover, this study introduces a reinterpretation of the replacement (B4) and refurbishment (B5) stages as defined by EN 15978. The distinction between these two stages—though essential to accurately calculate EE and waste over a building’s lifecycle—is not consistently addressed in the existing literature. Thus, the methodology developed here is based on a rational framework informed by material life cycles, but future research is needed to further validate and standardize these classifications across building types and geographies.

Although this study includes sensitivity analyses related to tenant turnover cycles and the assumed building service life, it does not incorporate a dedicated uncertainty or sensitivity analysis of the embodied carbon values. As embodied carbon assessments can be influenced by variations in input data, methodological assumptions, and emission factors, the absence of such an analysis represents a limitation. Future research should therefore explore uncertainty quantification and sensitivity analysis to enhance the robustness and generalizability of embodied carbon results.

3.9. Discussion

The results of this study emphasize that design flexibility can substantially reduce fit-out waste, embodied energy, and embodied carbon emissions in rentable office buildings. In the context of Türkiye, where the office market is concentrated in metropolitan areas such as Ankara and İstanbul, frequent tenant turnover intensifies material replacement cycles and resource depletion. The finding that flexible interior strategies can reduce embodied energy loss by over 80% suggests that waste prevention through design could play a critical role in achieving national resource efficiency goals.

Türkiye's Zero Waste Strategic Plan (2019–2023) and the National Climate Change Mitigation and Adaptation Strategy and Action Plan (2024–2030) both highlight the importance of circular economy practices in the construction sector. However, current regulatory frameworks primarily address waste management at the post-generation stage—through collection, recycling, and disposal—rather than prevention at the design phase. The outcomes of this study reveal that integrating spatial flexibility into design guidelines for rentable offices could complement these national policies by reducing refurbishment frequency and minimizing embodied carbon at the source.

Moreover, while international frameworks such as the European Green Deal and the United Nations Sustainable Development Goals (SDG 12: Responsible Consumption and Production) promote life-cycle thinking, there remains limited alignment between policy intent and design practice in emerging economies. By quantifying the environmental benefits of open-plan and modular partition systems, this study provides empirical support for shifting national building regulations from static performance metrics toward adaptable, circular design principles.

Overall, these results reinforce that environmental sustainability in the building sector cannot be achieved solely through material efficiency or end-of-life recycling. Instead, policies must recognize flexibility as a preventive strategy that reduces embodied impacts before they occur, thereby bridging the gap between design practice, building regulation, and circular economy goals.

4. Conclusion

High tenant turnover in rentable office buildings often necessitates frequent interior refurbishments, leading to substantial fit-out waste and increased raw material demand. These repeated changes exacerbate environmental impacts throughout the building's life cycle. Particularly in Türkiye, where waste management infrastructure is limited, implementing design-stage strategies is critical for mitigation.

This study compared standard and rentable office models to quantify waste generation and assess embodied environmental impacts. It also evaluated the effectiveness of two flexible design strategies—open plan layouts and movable partition walls—in reducing EE, embodied carbon (EC), and total waste. Results showed that open plan layouts reduced LCEE by 61.3%, EE loss by 64% and embodied carbon (EC) by 61%, primarily due to minimized use of interior partitions. Although movable partitions require higher initial EE, they achieved an 38.1% in LCEE, 84.3% reduction in EE loss, and 45.2% in EC by allowing reconfiguration without complete replacement of material.

A comprehensive assessment of total waste, LCEE, EE loss, EC, and component-specific impacts revealed that each design strategy offered distinct environmental advantages. Open plans were more effective in reducing overall LCEE, total and demolition waste, and EC across all life cycle stages. Movable partitions, on the other hand, excelled in minimizing fit-out waste and refurbishment-phase (B5) energy consumption.

At the component level, interior walls contributed the most to environmental impacts due to their extensive surface area and frequent alteration. Among wall materials, glass and MDF exhibited the highest embodied energy values, while gypsum board and glass contributed most to waste. However, MDF showed significant potential in minimizing EE loss due to its durability and reusability, aligning well with circular design principles.

In light of these findings, it is recommended that architects and designers prioritize materials based on their service life, reusability, and adaptability to evolving functional needs within office spaces. Emphasizing design strategies that minimize material replacement and support longevity can significantly reduce environmental impacts over the building's life cycle. Building owners and tenants should be made aware of the long-term operational and ecological benefits associated with flexible interior layouts and component choices. Furthermore, material manufacturers are encouraged to focus on the development of modular, demountable, and lightweight systems that facilitate disassembly and reuse, thereby supporting circular economy principles in the construction sector.

Future studies should delve into the performance of advanced flexible systems, such as dynamic walls, raised floors, and adaptive ceiling systems, within the life cycle context of commercial buildings. In addition:

- Empirical data collection through user surveys and interviews could provide grounded insights into material change patterns and tenant needs.
- Cost-benefit analyses integrating carbon and energy metrics can offer a holistic understanding of the trade-offs between initial investment and life cycle performance.
- Policy-level recommendations should focus on regulatory frameworks and incentives that promote material efficiency and low-waste interior design practices in rentable office markets.

By expanding awareness and applying informed design strategies, stakeholders can significantly reduce the environmental impact of the built environment, especially in high-density urban contexts.

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Author Contributions

E.K. Bakırhan: Conceptualization, Methodology, Software, Data curation, Writing- Original draft preparation, Visualization, Investigation, Validation. M.T. Kayılı: Project administration, Methodology, Supervision, Writing- Reviewing and Editing.

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Data Availability Statement

No new data were created or analyzed in this study.

Ethics Committee Permission

Not applicable.

Conflict of Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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