Cumulative climate impact of repeated tenant adaptations

Material Mass Intensity and Adaptation Depth

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Master thesis in Energy-efficient and Environmental Buildings
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Lund University

Lund University, with eight faculties and a number of research centres and specialized institutes, is the largest establishment for research and higher education in Scandinavia. The main part of the University is situated in the small city of Lund which has about 112 000 inhabitants. A number of departments for research and education are, however, located in Malmö. Lund University was founded in 1666 and has today a total staff of 6 000 employees and 47 000 students attending 280 degree programmes and 2 300 subject courses offered by 63 departments.

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The degree project is the final part of the master's program leading to a Master of Science (120 credits) in Energy-efficient and Environmental Buildings.

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Abstract

When greenhouse gas emissions in the building sector are considered, the focus is often on new construction. However, this is not the whole picture. Existing commercial buildings, such as office buildings, also go through several changes during their lifetime, and these changes can have a relevant climate impact. In office buildings, such changes are often called tenant adaptations, where the interior space is adjusted for current or future tenants. This can include changes to floors, interior walls, finishes, painting, installations, ventilation, and other building elements. A single tenant adaptation may seem small compared with a new building, but repeated adaptations can add up over time. Since climate thresholds and climate declaration requirements mainly address new construction, the climate impact of tenant adaptations is not controlled in the same way.

This thesis studies these issues by analysing the climate impact of tenant adaptations in office buildings. The study is based on project data provided by Wihlborgs Fastigheter AB and includes 27 tenant adaptation projects and two new construction projects used as reference cases. The analysis focuses on climate impact and material mass intensity for modules A1–A5. These modules were selected since they are used in the Swedish climate declaration approach.

The study examined how tenant adaptations can be classified by depth and material mass intensity was used for this calculation. Material mass intensity can give an indication of how much material is changed in each project, meaning that a higher material mass intensity can suggest a deeper tenant adaptation.

Based on the results, proposed threshold values were developed for light, moderate, and deep tenant adaptations to support better control of their climate impact. Several scenarios were developed. These included scenarios based on adaptation depth, a reuse and recycling scenario, and scenarios using the proposed threshold values for tenant adaptations.

The results show that repeated tenant adaptations can exceed the threshold values used for new construction over a 50-year reference study period. The results also show that deep adaptation is not automatically the worst option. A single deep adaptation may have a high impact, but several smaller adaptations can lead to a high cumulative climate impact when they are repeated over time.

This study shows that tenant adaptations should be considered more clearly in building life cycle assessment. Better project data is needed, and threshold values could help limit the climate impact of these projects. Future research should also study tenant adaptations in other contexts and include other aspects, such as cost and practical tools for assessment.

Preface

This thesis was carried out as part of the master's programme in Energy-efficient and Environmental Building Design at Lund University. The study focuses on the climate impact of tenant adaptations in office buildings and was developed using project data provided by Wihlborgs Fastigheter AB.

I would like to thank my supervisor, Jouri Kanters, for his guidance, fast feedback, and continuous support throughout the thesis process.

I would also like to thank Wihlborgs Fastigheter AB for providing the project data used in this study.

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1 Introduction

The demand for new construction and renovation continues to grow due to urbanization, economic development, and changing user requirements (Joint Research Centre, 2025). However, this development also results in higher environmental impacts. The building sector is responsible for a large share of global greenhouse gas emissions, currently at around 37 percent (UNEP, 2023).In recent years, strong efforts have been made to reduce operational energy use in buildings. As regulations for energy performance have become stricter, operational emissions have decreased in many countries (Röck et al., 2020).

This shift has also made embodied emissions from materials more important. Materials used for construction, renovation, and replacement now represent a larger share of total building-related emissions (GRESB, 2023). While these developments apply to multiple building types, office buildings present a particularly relevant case. Office buildings go through many stages during their lifetime (Chen et al., 2025).

One aspect in this process is tenant adaptations. Tenant adaptations can be understood as fit-out and refurbishment works carried out to adjust leased interior spaces to the needs of tenants (GRESB, 2025). These works may include changes to partitions, floor finishes, ceilings, lighting, electrical systems, and other interior components (GRESB, 2025). These adaptations require materials to be produced, installed and removed; these repeated adaptations can add embodied climate impacts over the building's reference study period. Current Swedish climate declaration regulation does not clearly address this issue, as the mandatory declaration applies to new buildings and covers the construction stage, modules A1–A5 (Boverket, 2022). Tenant adaptations can be carried out to extend the life of a building component. However, in office buildings, Tenant adaptations are often done to increase attractiveness for tenants (Jørgensen et al., 2025). In this context, interior components such as finishes, installations, and partition systems are replaced frequently. These repeated adaptations lead to additional material flows during the building's lifetime.

Life Cycle Assessment (LCA) is widely used to evaluate the environmental impact of buildings (Fahlstedt et al. 2024). But the way replacement and renovation emissions are modelled varies between studies and national frameworks. Since office buildings undergo frequent tenant adaptations, methodological assumptions may highly influence total climate impact results (Chen et al. 2025). This study investigates the extent to which service life assumptions and adaptations affect the totally embodied climate impact of a building over a defined reference study period.

This thesis explores tenant adaptation project data from office buildings to assess how repeated interior changes contribute to embodied climate impacts. The analysis focuses on material quantities, building element categories, and related CO_2 emissions.

1.1 Literature review

Chen et al. (2025) show that emissions from building component replacements can become large over longer reference study periods. In their case study, B4 replacement emissions reached 45% of the original A1–A3 production emissions from the building's first construction after 60 years and exceeded 90% after 100 years. These findings indicate that replacement has a significant environmental impact (BRE, 2018). There are several tools and methods to calculate these impacts enabling users to reduce the environmental impact.

Life cycle assessment (LCA) has become a central method for evaluating the climate impact of buildings over time. European standards (EN 15978) have structured the assessment into several boundaries: production, construction, use, and end-of-life stages (A-D). In practice, many studies and climate declarations focus mainly on the construction phase (A1-A5), as illustrated in recent Swedish reference value studies (Malmqvist et al.,2023) Currently in the EU, a large share of embodied emissions is connected to the initial construction stage. Previous work estimates that around 60–70% of embodied emissions come from materials used for initial building construction, also referred to as upfront embodied emissions (Science Based Targets initiative, 2024). This provides a structured baseline for new construction, but it does not fully capture the long-term impacts of buildings. The regulations in Sweden for operational energy have become stricter, which has led to a decrease the operational energy (Boverket, 2022.). The regulations for embodied energy are not clearly defined and are less strict. The United Nations Environment Programme (2023) raises the question of how the current framework can be further improved and which life cycle stages of the building should be included except the ones that are currently considered. Recent research shows that the B module in (LCA) boundaries are accepted in international standards but lacks detailed quantification methods (Chen et al., 2025). In Sweden, the B stage is not a mandatory requirement, but it has become more common over time. Many certification systems and programs currently require reporting of this stage, although no specific threshold is defined. (Sweden Green Building Council, 2024) (GRESB, 2026). This is closely linked to service life estimation as Denmark (Haugbølle et al., 2021) provides standardized service life values for building components to improve consistency in LCA. In contrast, Swedish practice allows greater flexibility in service life assumptions (Malmqvist et al.,2023). While flexibility allows adaptation, it may also introduce variation in replacement modeling. The lack of clarity in life cycle assessment does not end there. Challenges also occur in the definition of the functional unit. Research further shows that methodological choices, regarding the functional unit and system boundaries, vary across studies (Fahlstedt et al., 2024). This makes comparison difficult and may unclear the increasing effect of repeated component replacement over time. In Sweden, the functional unit is defined as the gross floor area in relation to CO_2 emissions (Malmqvist et al.,2023). By comparison (Attia et al., 2024) suggests the use of the system applied in the Netherlands, where the functional unit is expressed as emissions per gross floor area per year. A similar approach is also used in Denmark (Eberhardt et al., 2019) Since there is often limited clarity regarding system boundaries and no clearly defined functional unit or threshold, emissions may be underestimated compared to the actual material turnover (Attia et al., 2024). Considering increasing requirements and the current global situation, it is important to understand how different assumptions influence total LCA results.

1.2 Aim and Research Questions

The main aim of this thesis is to study how methodological choices in life cycle assessment (LCA) of tenant adaptations affect the results. Different assumptions in an LCA study, such as system boundaries, functional units, or thresholds, can change how tenant adaptations related emissions are calculated and interpreted. The thesis is guided by the following research questions:

- How do methodological choices influence decision-making in LCA studies of building tenant adaptations?
- Are there practical assumptions or choices in LCA studies that are not clearly documented?
- What role do emission thresholds play in the interpretation of tenant adaptations related to LCA results?
- To what extent do tenant adaptations activities contribute to emissions in building life cycle assessments?
- What approaches could help reduce emissions related to tenant adaptations activities?
- How are functional units defined in LCA studies of building tenant adaptations?

This study uses case studies of tenant adaptations in office buildings. Several individual cases were collected and analysed to compare and identify common patterns and to explore a possible reference approach for interpreting tenant adaptations emissions. Life cycle assessment is used as the main analytical framework in this study.

2 Methodology

This chapter describes the methods used in the project. It first explains how the project data was collected and prepared. It then describes how material mass and climate impact were estimated. Finally, it explains how the tenant adaptations were classified and how the results were compared between the projects.

2.1 Data collection

The data used in this study was provided by Wihlborgs Fastigheter AB. Wihlborgs is a Swedish property company focused on commercial properties in Malmö, Lund, Helsingborg, and Copenhagen. In 2024, the company owned 307 commercial properties with a total area of 2.3 million m² and around 2,000 tenants. Wihlborgs has climate targets to reduce greenhouse gas emissions by 50% by 2030 and to reach net-zero emissions across its operations by 2045. The company also states that it aims to design flexible premises that can be adapted to new needs over time, which makes tenant adaptations relevant for property management and climate impact assessment (Wihlborgs, 2024). According to information provided during the company interviews, projects below approximately SEK 1 million were mainly described as maintenance related, projects above this level were treated as more substantial tenant adaptation works.

The collaboration with the company made it possible to access real project data from office building projects and tenant adaptations. The data collection was carried out through meetings, interviews, and email communication with company representatives. Several meetings were held online, and some information was also discussed in person. The sustainability department was the main contact point and helped collect information from other departments when additional project knowledge was needed.

In total, 29 projects were included in the study. Of these, 27 were tenant adaptation projects and 2 were new construction projects used as reference cases. All analysed projects were office related buildings or office tenant adaptations. The projects differed in size, scope, and level of data detail. The dataset was selected based on the available project material and its relevance for analysing tenant adaptation climate impact. All project names and building identities were anonymised before the analysis.

Table 1 Number of projects

Project group	Number of projects	Role in analysis
Tenant adaptations	27	Main dataset
New construction	2	Reference comparison
Total	29	Full analysed dataset

2.2 Data preparation and analysis

All project data was organized and analysed using Microsoft Excel. The data was based on Excel template results provided by the company. From each template, the total climate impact, building area, building element categories, material quantities, and reported climate impact per category were extracted. These values were then placed in one comparison file. This made it possible to compare all projects using the same structure.

The analysis was carried out at two levels: project level and building element level.
First, the projects were analysed at project level. This was done by comparing the total climate impact and the total material mass intensity between the projects. This step was used to see which tenant adaptations had low or high overall results.

Second, the projects were analysed at building element level. The results were divided into categories such as groundworks, substructure, frame, room formation, interior finishes, and installations. This step was used to see which building elements contributed most to the climate impact and material mass intensity. By using both levels, it was possible to compare the projects as whole adaptations and understand which parts of the projects caused the differences between them.

Before the analysis, the data was reviewed. During the data review, some inconsistencies were found and corrected where possible. Some projects were reported two times at different stages in the templates. These were checked so the projects could be compared more fairly. In some templates, both detailed material data and default (schablon) values were included. This could lead to double counting, so these cases were reviewed and adjusted when the overlap was clear. When information was missing, the available values from the templates were used.

2.3 Templates

The project data were provided in Excel-based climate calculation templates. The templates had been developed at Wihlborgs to calculate climate impact for new construction, renovation, and tenant adaptation projects. They follow an LCA structure based on modules A1–A5, including product stage impacts, transport to site, and construction-related impacts.

The template is divided into several worksheets. One worksheet describes the calculation method and general requirements, including the use of EN 15978 for buildings and EN 15804 for construction products. It also states that the climate impact should be reported as GWP-GHG and expressed per square meter of gross floor area.

The template requires that the calculation includes most of the relevant materials in the project. As a minimum, the materials included should represent more than 80% of the relevant material weight. This is to ensure that the calculation is not based on only a small part of the project. The material quantities are organised according to the SBEF building element table, based on BSAB 83.

Two worksheets (tender stage ("anbud") and verification stage ("verifiering")) in the template were used for entering the materials and building components included in the project. The tender stage represents early estimates prepared before construction, often based on general assumptions. The verification stage shows the final stage after construction, where the material data is more detailed and based on actual quantities used.

In these sheets, each material is entered with information such as product name, building element category, product category, quantity, conversion factor, mass, emission factor, and transport data. The template then calculates the climate impact for each material and summarizes the result by building element category.

When both tender-stage and verification-stage values were available, the more detailed one was preferred. If both stages had a similar level of detail, the verification-stage values were preferred because the verification stage is closer to the final project, since early estimates can include more assumptions, while verified values are usually based on more complete material information. If only tender-stage values were available, these were used.

Several background data sheets are included in the template. These contain generic climate data, transport factors, building element categories, and resource categories. For the climate data, it was possible to either use generic emission factors from Boverket's climate database or enter project-specific values based on Environmental Product Declarations (EPDs). This allowed the calculation to be carried out with either standard reference values or more detailed product-specific data when available. However, it was recommended to use the specific EPD data when it was available, especially in the verification stage.

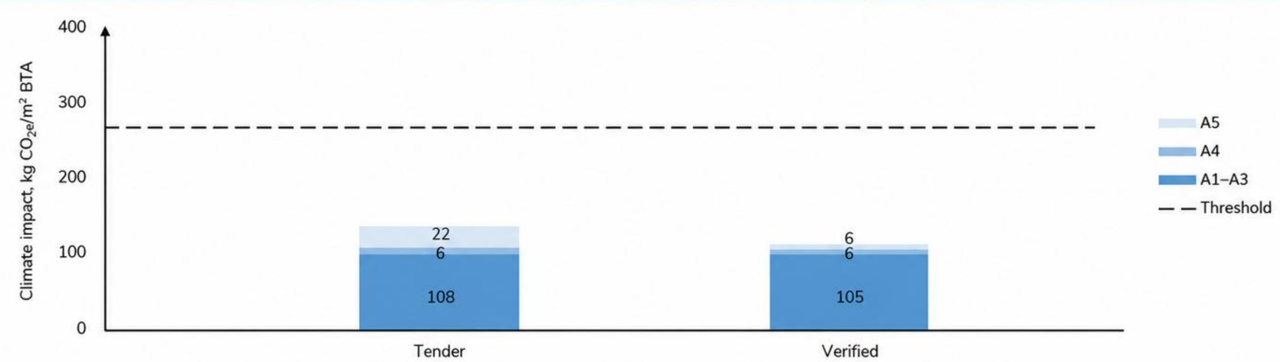
The generic climate data made it faster to enter values in the template. The user could select a material directly in the template, and the template then calculated the climate impact automatically. As mentioned, this was useful when detailed product data was not available. However, a limitation of the generic values is that they are conservative values. These values include a 25% increase compared with typical values, which means that they can give higher climate impact results than product-specific EPD data. Therefore, projects based mainly on generic values may show higher emissions than projects where more detailed EPD data was used.

A summary worksheet was used to present the results of each building. The summary worksheet presents the main project information, such as project name, building type, location, gross floor area, heated floor area, and the threshold value. It should be noted that the threshold value shown in the template referred to new construction. It also shows the total climate impact for modules A1–A5 and separates the results into A1–A3, A4, and A5. In this part of the template, the calculated result is compared with the threshold value.

Project details

Project name	----			Wihlborgs project number	....
Project type	Refurbishment				
Property description	----			Location	Malmö
Building type	Logistics/Production				
Gross floor area (BTA), m^2	1670	No. of floors	1	Energy rating	90x
Heated floor area (A_{heated}), m^2	1670	Threshold for climate impact for building stock, kg CO_2e/m^2 BTA			270

Climate impact per life cycle stage under building stage, A1–A5



Life cycle stage			Tender: Climate impact (kg CO_2e/m^2 BTA)		Margin to threshold	Verified: Climate impact (kg CO_2e/m^2 BTA)		Margin to threshold
A1–A3		Product	107.6		50%	105.3		57%
A4		Transport	6.3			5.9		
A5	A5.1	Construction process	21.5	7.5		5.9	5.3	
	A5.2	Energy use during construction		14.0			0.0	
	A5.3	Other		NMD			NMD	
Total			135			117		

The threshold is based on the target value for maximum climate impact of the building stock in Wihlborgs Fastigheter AB's environmental program.

Figure 1 shows one part of the summary worksheet in the climate calculation template.

2.4 Building element classification

This BSAB classification system was used to group building materials and components into building element categories. In this thesis, the categories were translated and simplified, as shown in Table 2.

Table 2 presents the building element categories used in the analysis. The table shows the main category code, the English category name, and a short description of what each category includes. This classification made it possible to analyse the results at building element level. It was used to compare which parts of the tenant adaptations contributed most to the climate impact and material mass intensity.

Table 2 Overview of building element categories used to classify tenant adaptation data.

Code	Building element category	Description
0	Demolition and removal	Demolition works, removal of building components
1	Ground works	Excavation, filling, drainage, ground reinforcement, roads, landscaping
2	Substructure	Foundations, ground slabs, garages, underground structures
3	Structural frame	Structural frame, columns, beams, floor slabs, stairs, elevator shafts
4	Roof	Roof structure, roof covering, roof edges, metal sheets, terraces
5	Facade	Exterior walls, facade cladding, windows, doors, gates
6	Structural complements / room formation	Interior walls, partitions, suspended ceilings, interior doors
7	Interior finishes / room complements	Floor finishes, wall finishes, painting, cabinets, interior fittings
8	Building services installations	Heating, ventilation, cooling, electrical systems, control systems
9	Common works	General construction works and shared processes

The first digit shows the main building element category. For example, category 6 refers to structural complements and room formation, and category 7 refers to interior finishes and room complements. The system can also include more detailed subcategories. For example, within category 6, subcategories such as 61, 62, and 63 describe more specific parts of the building element group. The same logic is used for other categories, such as 7, where 71, 72, and 73 describe more detailed interior components. In the Wihlborgs templates, materials could be entered at this more detailed subcategory level. To make the projects comparable, the detailed subcategories were grouped into the main building element categories used in this study.

2.5 Building element benchmarking

To better understand the extent of the tenant adaptation, the analysis tested the material mass connected with the building elements shown in Table 2. Each category was analysed separately. Since material mass may reflect the physical scale of the intervention within each building element, material mass was used as an indicator of tenant adaptation extent. Climate impact shows the environmental result, and material mass intensity shows the physical amount of material involved in the adaptation. By using both, it was possible to see if a project had high emissions because it involved more material, or because the materials had high emission factors.

The total mass (kg) and mass per gross floor area (kg/m^2 BTA) were considered to allow comparison between projects of different sizes. The material quantities from all tenant adaptation projects were collected and average values were calculated. These averages were then compared across the dataset to identify typical ranges for each category. Based on these average results, the relation between mass and emissions was checked to interpret the results.

After the project data had been analysed and averaged, the values were used to define typical material intensity ranges. These ranges then formed the basis for the benchmarking and adaptation depth classification. Since different building elements have different typical material quantities, each category was benchmarked individually. The comparison was always carried out within the same category and in the projects where this specific data was available to avoid misleading results.

The tenant adaptation projects were also compared with the two new construction reference projects. The average of these two new construction projects was used as a reference point. This made it possible to see how much the tenant adaptations differed from initial construction, in material mass and climate impact.

The comparison was not used as a fixed standard, since only two new construction projects were available. Instead, it was used as a supporting reference to check whether the tenant adaptation results were reasonable and to show the difference between tenant adaptations and new construction at project level and building element level.

A climate impact benchmark was also developed for each building element category. This was used to check whether the climate impact of a specific category exceeded the proposed category-level threshold. If a threshold was exceeded, the category was highlighted in the adapted template. This gave direct feedback on which building element category was responsible for a high result.

2.6 Adaptations classification and threshold definition

To classify the tenant adaptation projects, a point based scoring method was developed. The scoring was based on the material mass intensity in each building element category, expressed as kg/m² BTA.
For each project, the material mass intensity in each category was compared with predefined threshold values. If the category remained below the light threshold, it received 1 point. If it reached the moderate threshold, it received 2 points. If it reached the deep threshold, it received 3 points.

Table 3 Material mass intensity thresholds used for the adaptation depth classification.

Result in category	Points
Low material intensity	1
Medium material intensity	2
High material intensity	3
Very high / default-heavy value	8

A separate high-impact criterion was also used. If one category exceeded this highest threshold, it received 8 points and the whole project was classified as deep. When default values were used in a building element category, that category was treated as deep in the classification. This was done because default values do not provide the same level of detail as project-specific material quantities. The choice was conservative and was used to avoid underestimating adaptation depth when detailed material data was missing.

After scoring all building element categories, the points were summed to give a total adaptation score for each project. The total score was then used to classify the project as light, moderate, or deep. Projects with lower total scores were classified as light adaptations. Projects with scores above 11 and up to 14 were classified as moderate adaptations, while projects with scores above 14 were classified as deep adaptations. This method means that a project can be classified as deep in two ways: either several categories have medium or high material intensity, or one category has a very high material intensity.

Table 4 Point system used for adaptation-depth classification.

Category result	Points	Interpretation
Below light threshold	1	Light contribution
Reaches moderate threshold	2	Moderate contribution
Reaches deep threshold	3	Deep contribution
Exceeds highest category threshold	8	Automatic deep classification

Table 5 Total score used to classify tenant adaptation depth.

Total score	Project classification
≤ 11	Light adaptation
> 11 to 14	Moderate adaptation
> 14	Deep adaptation
Any category with 8 points	Whole project becomes deep

The total score limits were selected after reviewing the score distribution in the dataset. They were used to separate the projects into three interpretable groups with increasing material mass intensity. Therefore, the limits should be understood as dataset-based thresholds rather than final industry benchmarks.

2.7 Reuse and recycling sensitivity scenario

A reuse and recycling sensitivity scenario was calculated to estimate how much the climate impact could be reduced if some materials were reused or recycled. The scenario was applied only to selected materials where reuse or recycling was considered more realistic, mainly interior-related materials. It should be noted that to calculate the reuse impact, only projects with enough detailed information were selected. Projects without enough material detail were not included in this scenario, because it was not possible to identify which materials could realistically be reused or recycled. Therefore, the scenario was applied only to projects where the material list allowed a basic selection of reusable or recyclable materials.

The calculation was done in three steps. First, the materials that could potentially be reused or recycled were selected. Second, the climate impact of these selected materials was compared with the total A1–A3 climate impact of the project. This showed how large part of the project impact came from the selected materials. Third, a 40% reduction factor was applied to this selected share. For example, if the selected materials represented 50% of the A1–A3 climate impact, the estimated subtraction was calculated as 50% × 40% = 20%. This means that the total A1–A3 impact of the project would be reduced by 20% in the scenario.

After calculating every possible project, the average of the benefit reduction was selected. This method is only a simplified sensitivity calculation. The 40% reduction factor was selected as a simplified scenario value to represent a partial reduction in production-stage impacts for materials assumed to be reused or recycled. The actual reduction would depend on material type, condition, transport, processing, and the product replacement.

The reuse potential and benefit factor were applied as a sensitivity scenario to explore how the results could change if part of the material flow were reused in future tenant adaptations.

2.8 Cumulative tenant adaptation scenario

A cumulative tenant adaptation scenario was developed to calculate the climate impact over a 50-year period. The timing and adaptation depth were based on information provided by Wihlborgs. The assumed sequence is shown in Table 5.

The scenario was evaluated over a 50-year reference period, with repeated adaptations occurring up to year 45. No additional adaptation was added at year 50, because the final interval represents the end of the reference period.

The scenario assumes that tenant adaptations occur every five years until year 45, moderate adaptations are included every 10 years, and one deep adaptation is assumed at year 30. No additional adaptation is included in year 50, as this marks the end of the reference study period. The assumed sequence is shown in Table 5.

Table 6 Adaptation depth used in the cumulative tenant adaptation scenario.

Year	Adaptation depth
5	Light
10	Moderate
15	Light
20	Moderate
25	Light
30	Deep
35	Light
40	Moderate
45	Light

The sequence shown in Table 5 was based on information from the company interviews and was used as a scenario calculation for the 50-year reference period. Only one deep adaptation was included at year 30 as a conservative assumption, although deeper adaptations could occur more than once over such a long period. The aim was to show the possible cumulative climate impact of repeated tenant adaptations over time.

For each adaptation depth, a climate impact value was assigned in kg CO_2e/m^2 BTA. The cumulative climate impact was calculated by adding each adaptation to the previous total. For example, the value at year 20 includes the adaptations at years 5, 10, 15, and 20.

It should be noted that the company descriptions of small, medium, and large tenant adaptations were useful to understand typical intervention cycles in practice. However, these categories do not always correspond directly to climate impact levels, since projects with different technical scopes may show similar emissions depending on the quantity and type of materials replaced.

2.9 Functional unit and result interpretation

The main functional unit used in this study is kg CO_2e/m^2 BTA. This follows the format used in the project templates and allows the tenant adaptation projects to be compared on the same area basis.
A time-based system was also tested to see how the results change when the assumed break between adaptations is included, since tenant adaptations can have different expected repetition periods depending on their depth. Selected threshold values were therefore expressed as kg CO_2e/m^2 BTA/year by dividing them by assumed time intervals. Other possible reference values, such as occupancy, were considered but not applied, since consistent occupancy data was not available for the analysed projects.

2.10 Use of reference values

For some building element categories, predefined reference values, called default values, were used. These are standard values for emissions and material quantities when detailed project data is not available. They are often used in early project stages or when exact material quantities are difficult to collect (IVL Svenska Miljöinstitutet, 2024).

In the templates, default values were used when project data was missing or incomplete. In some templates, these values were already included together with other project data. These cases were checked during the data review to reduce the risk of double counting. Values from the IVL Svenska Miljöinstitutet (2024) report were also reviewed to understand typical ranges for tenant adaptation projects. However, they were not used directly in calculations. They were only used as background reference when interpreting the results. A limitation of default values is that they are based on average assumptions. Therefore, they may be higher or lower than the actual values for a specific project.

2.11 Limitations

The study has several limitations that should be considered when interpreting the results. First, the dataset is limited to office related projects from one property company. The results are useful for understanding the analysed cases, but they should not be used as general values for all tenant adaptations without further testing.

Second, the results depend on the quality and completeness of the project templates. The collected material data was not always detailed enough, and some projects had more complete information than others. Some values were based on assumptions or existing reference values. If the material quantities and material types are not clear, it becomes difficult to understand where the emissions come from.

Third, the proposed adaptation depth thresholds were developed from this dataset. They should therefore be understood as a first suggested classification method, not as final industry benchmarks. More projects would be needed to test whether the same threshold levels are suitable in other contexts.

Finally, the reuse and cumulative scenarios are simplified. They are useful for testing possible effects, but they do not represent measured future outcomes. The results should therefore be read as scenario-based interpretations rather than exact predictions.

3 Results

This chapter presents the results from the analysis of all projects. The results are organised to show the overall variation between projects and the more detailed differences between building element categories.

The chapter first presents climate impact and material mass intensity as two related indicators. Climate impact shows the emissions from the projects; material mass intensity helps describe the physical scale of the adaptations. These results are then used to support the classification of tenant adaptations into light, moderate, and deep interventions.

The final part of the chapter presents scenario results for reuse and recycling, repeated adaptations, and time-based interpretation. These scenarios are used to test how the results change when reuse potential and repeated interventions over time are considered.

3.1 Climate impact results

This section presents the climate impact results of the analysed tenant adaptation projects. The results are shown at project level and then by building element category to identify where the main climate impacts occur.

3.1.1 Total climate impact per project

Figure 2 shows the total climate impact of the analysed tenant adaptation projects, expressed as kg CO_2e/m^2 BTA. The red dashed line shows Wihlborgs' future climate target of 142 kg CO_2e/m^2. The current new construction threshold of 270 kg CO_2e/m^2 is not included, since it lies outside the useful scale of the figure.

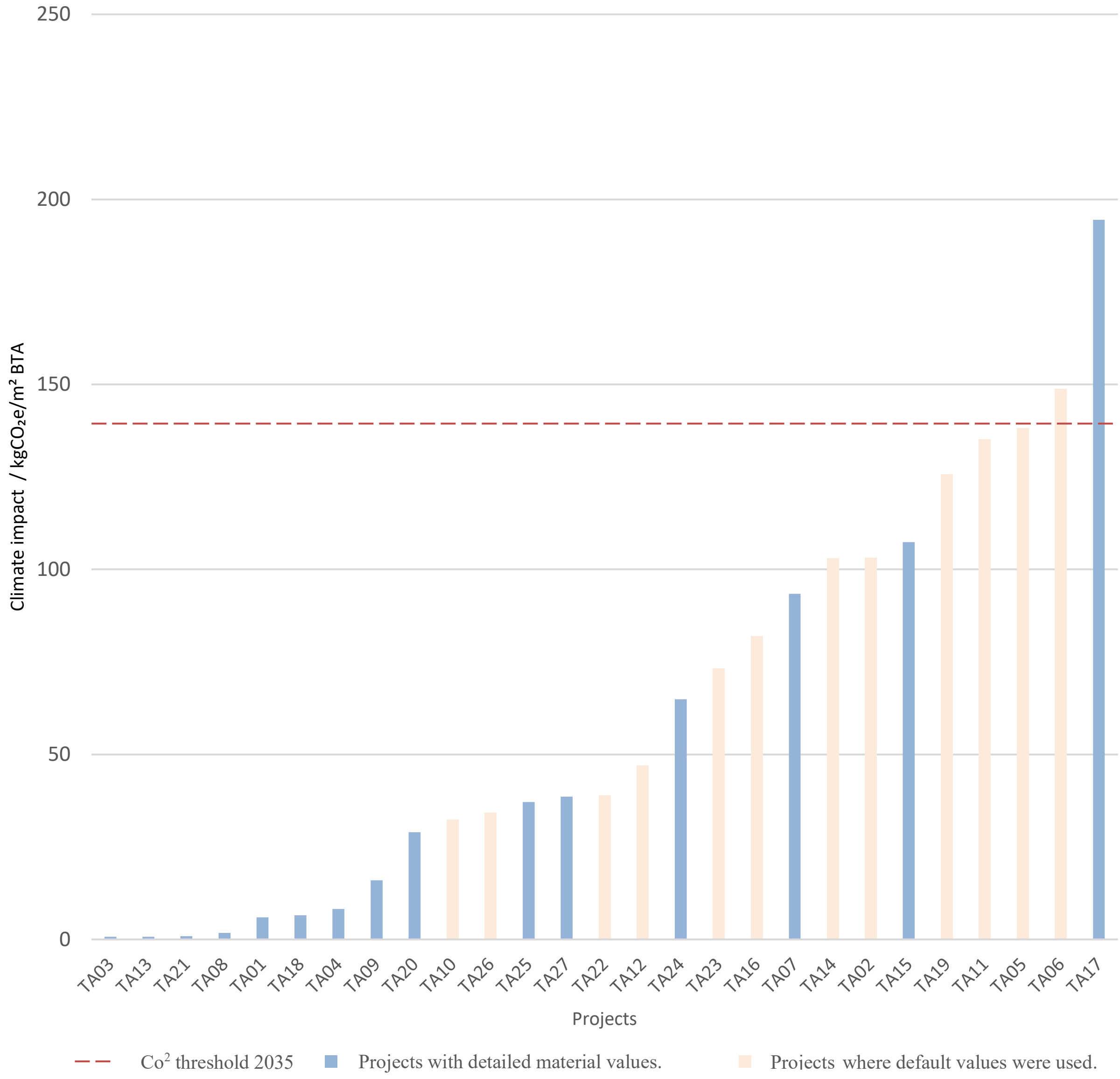


Figure 2 Total climate impact per project, expressed as kg CO_2e/m^2 BTA for modules A1–A5.

The tenant adaptation projects show a wide variation. Several projects have very low reported impacts, while a smaller number of projects show higher values. The highest result is found for TA17, which shows that some tenant adaptations can have a high climate impact.

3.1.2 Climate impact by building element category

Figure 3 shows the average climate impact by building element category for the tenant adaptation projects. The figure is used to identify which parts of the adaptations contribute most to the total climate impact.

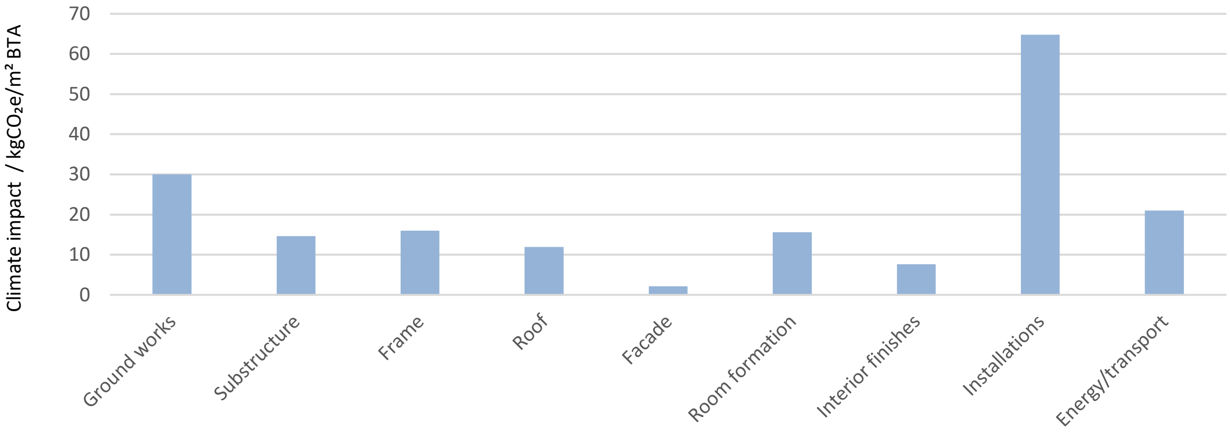


Figure 3 Average climate impact by building element category, expressed as kg CO_2e/m^2 BTA for modules A1–A5.

Installations have the highest average climate impact, followed by groundworks and energy and transport. Other categories, such as frame, room formation, substructure, and roof, show lower average values. Facade has the lowest average impact in this dataset. Demolition and removal works were excluded from this figure, since they were not included in the climate impact calculations.

3.1.3 Frequency of building element categories in tenant adaptations

Figure 4 shows which building element categories are most frequently included in the analysed tenant adaptation projects.

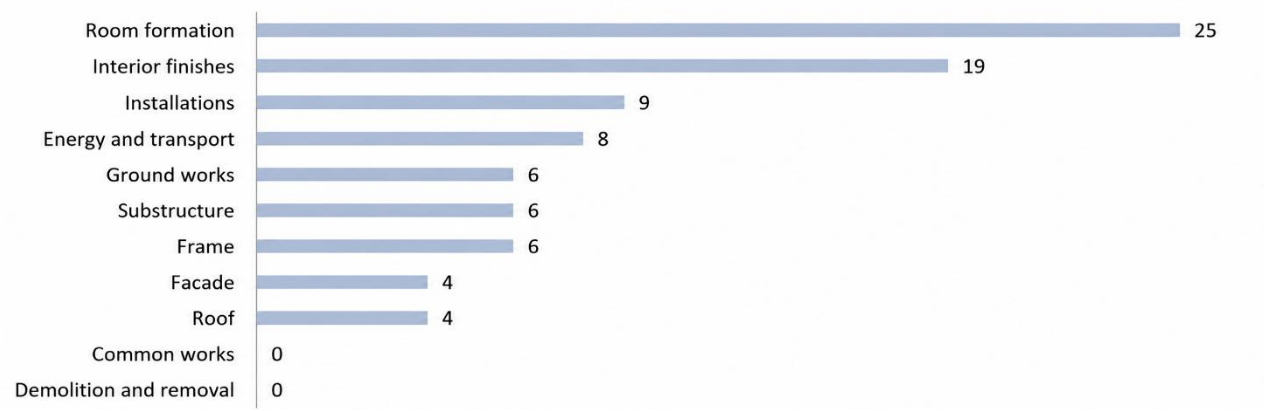


Figure 4 Number of tenant adaptation projects with reported values in each building element category.

Room formation and interior finishes are the most frequently reported categories, which shows that the projects are mainly concentrated on interior spatial changes. Installations are reported less often, but they still appear in several projects. Categories related to the main building structure and envelope, such as frame, roof, and facade, occur only in a limited number of cases. This pattern reflects the typical scope of tenant adaptations, where most work takes place inside the existing building rather than in the structural or external parts.

3.1.4 Climate impact threshold results by category

Table 6 shows the category-level climate impact threshold values used in the adapted template. The highest threshold values were assigned to room formation and installations. The lowest threshold values were assigned to roof and facade.

Table 7 The category-level climate impact threshold values

Ground works	Substructure	Frame	Roof	Facade	Room formation	Interior finishes	Installations	Energy/transport
10	10	10	5	5	15	8	15	10

The threshold values in Table 7 were then used in the adapted template. If the climate impact of a building element category exceeded its selected threshold value, the corresponding cell was highlighted in red. This function was included to make it easier to identify which categories were responsible for high climate impact results.

	0 Demolition and stripping	1 Ground works	2 Substructure	3 Frame	4 Roof	5 Facade	6 Room formation / frame complements	7 Interior finishes	8 Installations	9 Common works	10 Energy and fuel
Climate impact (kg CO₂e/m² BTA)	0.0	0.0	35.2	18.1	16.5	3.6	59.6	5.5	0.0	0.0	0.0
Climate impact (kg CO₂e)	0.0	0.0	35,201.3	18,141.4	16,504.4	3621.0	59,570.9	5544.0	0.0	0.0	0.0
Climate impact (kg CO₂e/m² BTA)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	28.0	87.0	0.0	0.0
Climate impact (kg CO₂e)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	28,000.0	87,000.0	0.0	0.0

Red	=	Deep

Figure 5 shows how the template highlights categories that exceed the selected threshold value.

3.2 Material mass intensity results

This section presents the material mass intensity results for the tenant adaptation projects and compares the physical amount of material used across projects and building element categories.

3.2.1 Material mass intensity per project

Figure 6 shows the material mass intensity for each analysed project, expressed as kg/m² BTA. The figure is used to compare the physical amount of material involved in each tenant adaptation and to show how these values differ from the new construction reference projects.

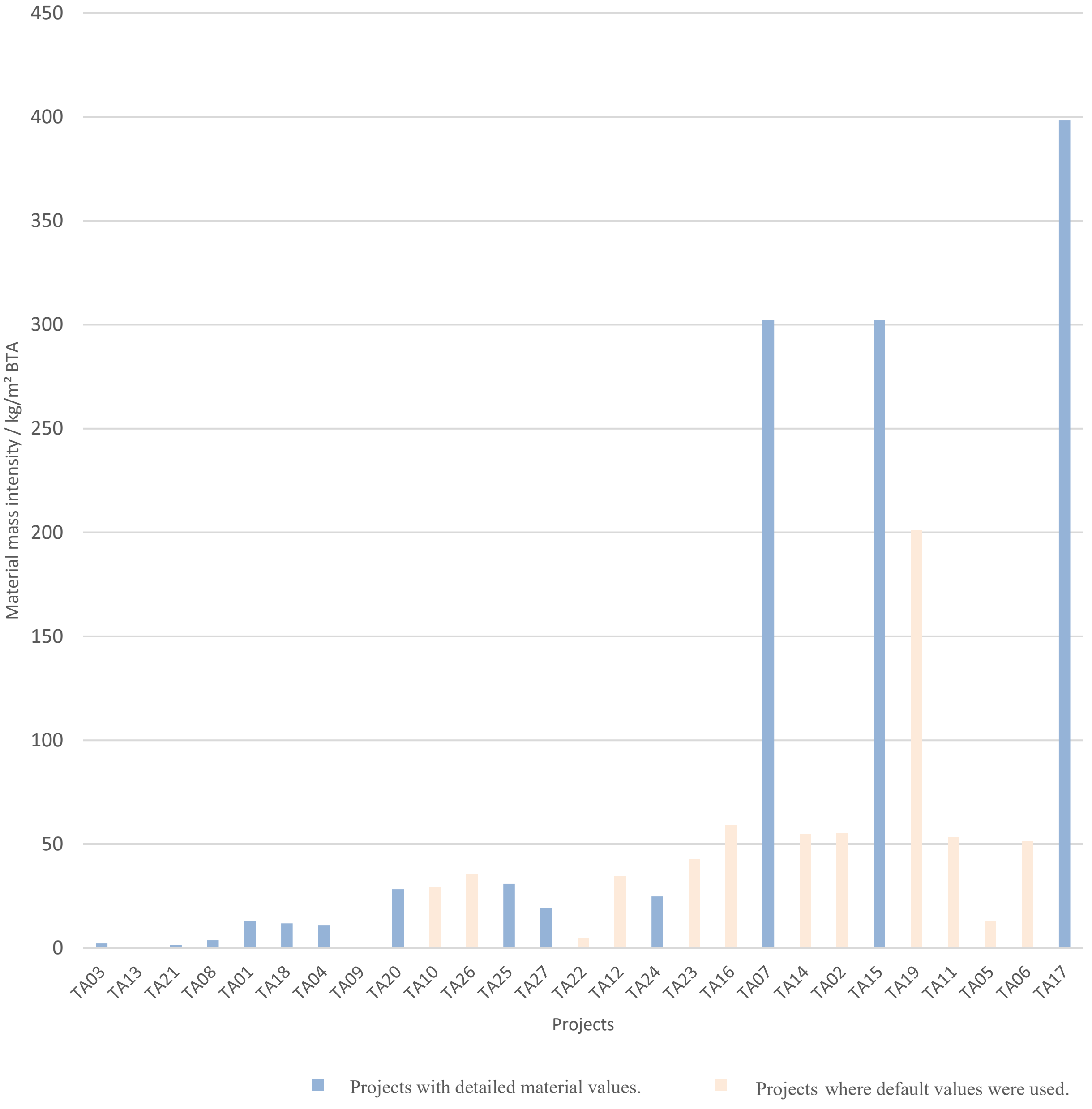


Figure 6 Material mass intensity per project, expressed as kg/m² BTA.

The tenant adaptation projects show a wide range of material mass intensity. Several projects have very low reported material quantities, while a smaller number of projects show higher values.

Figure 7 shows the average material mass intensity by building element category, expressed as kg/m² BTA. Energy and transport is excluded because this category does not have material mass intensity.

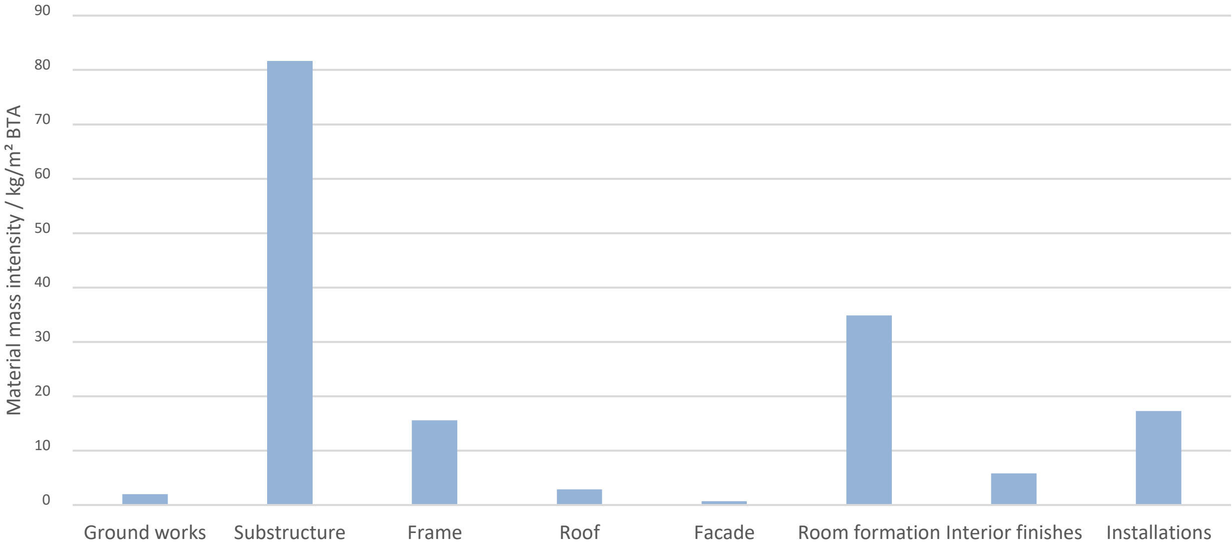


Figure 7 Average material mass intensity by building element category, expressed as kg/m² BTA.

Demolition and removal and common works are also excluded, since they have no reported material values in the analysed tenant adaptation projects. The highest average mass intensity is found in substructure, followed by room formation and installations. Frame also contributes to the average material mass intensity, while ground works, roof, facade, and interior finishes show lower values.

3.3 Classification of tenant adaptation depth

This section presents the classification of tenant adaptation depth based on the relationship between climate impact and material mass intensity. The classification is used to divide the projects into light, moderate, and deep tenant adaptations.

3.3.1 Relationship between climate impact and material mass intensity

Figure 8 shows the relationship between material mass intensity and climate impact for all the analysed projects. Blue points show tenant adaptations and the orange points show tenant adaptations with default values.

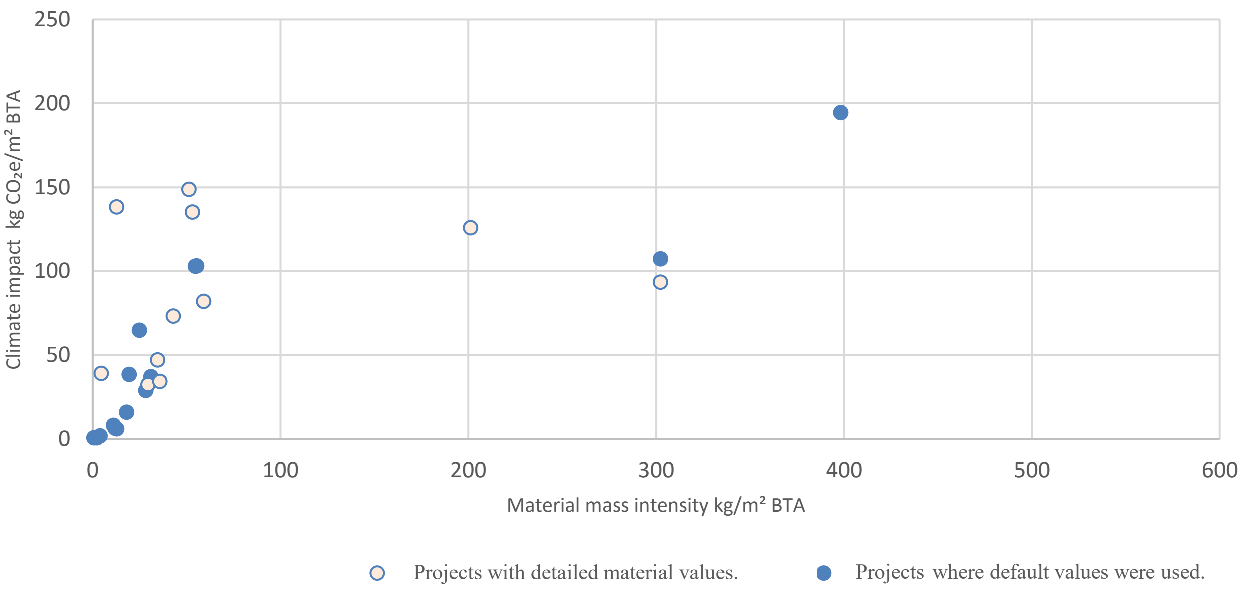


Figure 8 Relationship between material mass intensity and climate impact for the analysed projects.

Each point represents one project. The results show that projects with higher material mass intensity often have higher climate impact, but the relationship is not consistent for all projects. Some tenant adaptation projects have relatively low material mass intensity but still show high climate impact. This can be linked to the use of default values. The two new construction reference projects are in the upper-right part of the figure, with both high material mass intensity and high climate impact.

3.3.2 Material mass intensity thresholds

Table 8 presents the material mass intensity thresholds used to classify the tenant adaptation projects. The values are expressed as kg/m² BTA.

Table 8 Material mass intensity thresholds by building element category, expressed as kg/m² BTA.

Category	1 point	2 points	3 points	8 points
Ground works	≤ 5 kg/m²	> 5 to 15 kg/m²	> 15 to 30 kg/m²	> 30 kg/m²
Substructure	≤ 6 kg/m²	> 6 to 15 kg/m²	> 15 to 30 kg/m²	> 30 kg/m²
Frame	≤ 6 kg/m²	> 6 to 15 kg/m²	> 15 to 30 kg/m²	> 30 kg/m²
Roof	≤ 3 kg/m²	> 3 to 6 kg/m²	> 6 to 12 kg/m²	> 12 kg/m²
Facade	≤ 2 kg/m²	> 2 to 4 kg/m²	> 4 to 9 kg/m²	> 9 kg/m²
Room formation	≤ 6 kg/m²	> 6 to 15 kg/m²	> 15 to 30 kg/m²	> 30 kg/m²
Interior finishes	≤ 3 kg/m²	> 3 to 6 kg/m²	> 6 to 10 kg/m²	> 10 kg/m²
Installations	≤ 4 kg/m²	> 4 to 8 kg/m²	> 8 to 17 kg/m²	> 17 kg/m²

The first threshold separates light and moderate adaptations, and the second threshold separates moderate and deep adaptations. The final threshold is used as an automatic deep adaptation criterion. If one building element category exceeds this value, the whole project is classified as deep, even if the total material intensity of the project is lower.

3.3.3 Classification results

Table 9 presents the climate impact of the tenant adaptation projects after they were divided into light, moderate, and deep adaptation groups.

Table 9 Summary of tenant adaptation depth classification.

Light	kg CO_2e/m^2 BTA
TA21	0.9
TA18	6.5
TA13	0.7
TA09	16
TA08	1.8
TA04	8.2
TA03	0.7
TA01	6.0
Total	Average
8	5.1

Moderate	kg CO_2e/m^2 BTA
TA27	38.6
TA26	34.3
TA25	37.1
TA24	38.9
TA22	47.0
TA20	32.3
TA12	64.5
TA11	29.0
Total	Average
8	40.2

Deep	kg CO_2e/m^2 BTA
TA23	73.2
TA19	125.2
TA17	194.3
TA16	81.1
TA15	107.0
TA14	103.2
TA10	135.1
TA07	93.0
TA06	149.3
TA05	138.2
TA02	103.0
Total	Average
11	118.3

The light and moderate groups each include 8 projects, while the deep group includes 11 projects. The average climate impact increases from 5.1 kg CO_2e/m^2 BTA for light adaptations to 40.2 kg CO_2e/m^2 BTA for moderate adaptations and 118.3 kg CO_2e/m^2 BTA for deep adaptations.

Figure 9 shows the distribution of climate impact for the three adaptation depth groups. The results are presented as a box plot to compare the range, median, and spread of values within each group.

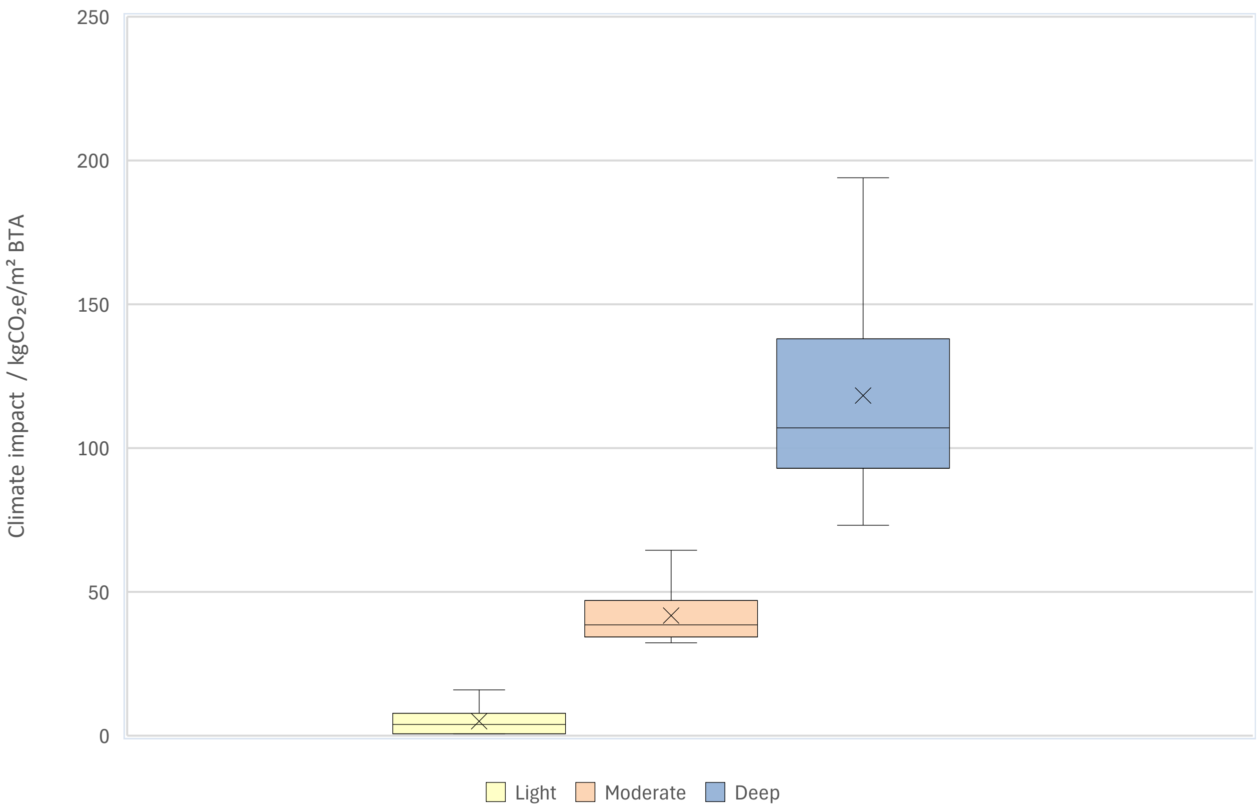


Figure 9 Distribution of climate impact by tenant adaptation depth.

The box plot shows a clear increase in climate impact from light to moderate and deep adaptations. Light adaptations have very low values compared with the other groups. Moderate adaptations show higher values, while deep adaptations have the highest values and the widest spread. This indicates that deeper adaptations generally lead to higher climate impact, although the variation within the deep group is also larger.

3.4 Reuse and repeated adaptation scenarios

This section presents the scenario-based results used to test how tenant adaptation impacts may change under different assumptions. The first scenario examines the possible effect of reuse and recycling, while the second scenario estimates the cumulative impact of repeated tenant adaptations over time.

3.4.1 Reuse and recycling sensitivity scenario

Table 10 presents the estimated climate impact reduction from a reuse and recycling scenario for selected tenant adaptation projects. The scenario estimates how much climate impact could be reduced if selected interior related materials were reused or recycled.

Table 10 Estimated climate impact reduction from a reuse and recycling scenario for selected tenant adaptation projects.

Case ID	Reuse/recycling mass share (%)	Selected A1–A3 impact (kg CO_2e)	Total A1–A3 impact (kg CO_2e)	Selected A1–A3 share (%)	Benefit factor (%)	Estimated reduction (%)
TA15	13%	26304	52804	50%	40%	20%
TA18	6%	16080	40079	40%	40%	16%
TA14	10%	287	1421	20%	40%	8%
TA17	6%	16080	40079	40%	40%	16%
TA19	22%	7540	16663	45%	40%	18%
TA24	24%	616	1536	40%	40%	16%
TA27	15%	1117	4105	27%	40%	11%
TA02	10%	968	7474	13%	40%	5%
TA04	11%	3235	4702	69%	40%	28%
TA06	73%	59730	65227	92%	40%	37%
TA05	5%	241	1027	24%	40%	9%
Average	18%	12018	21374	42%	40%	17%

The calculation is based on the share of material mass assumed to be reusable or recyclable, the selected A1–A3 impact, and a benefit factor of 40%. The average reuse/recycling mass share is 18%, the average selected A1–A3 share is 42%. Based on these assumptions, the estimated average reduction is 17%. The results represent a scenario rather than measured project outcomes. The reduction depends strongly on which materials are assumed to be reusable or recyclable and on the selected benefit factor. Therefore, the table is mainly used to test the possible effect of reuse and recycling on the tenant adaptation results.

3.4.2 Repeated tenant adaptation scenario and the new thresholds

The following scenario values represent how different assumed climate impact levels affect cumulative results.

Table 11 Repeated tenant adaptation scenario used in the cumulative climate impact calculation.

Scenario	Light adaptation ($kgCO_2e/m^2$)	Moderate adaptation ($kgCO_2e/m^2$)	Deep adaptation ($kgCO_2e/m^2$)
Low scenario	3	30	80
Medium scenario	5	40	110
Upper scenario	10	50	138
Proposed threshold	6	35	100
Proposed + reuse	4.92	28.7	82

Table 11 presents the climate impact values used in the repeated tenant adaptation scenarios. The values are divided into light, moderate, and deep adaptations, based on the adaptation depth classification. The low, medium, and upper scenarios represent different assumed climate impact levels within each adaptation type. The proposed threshold scenario is used to test a limited cumulative impact case, the proposed + reuse scenario includes the estimated reduction from the reuse and recycling scenario.

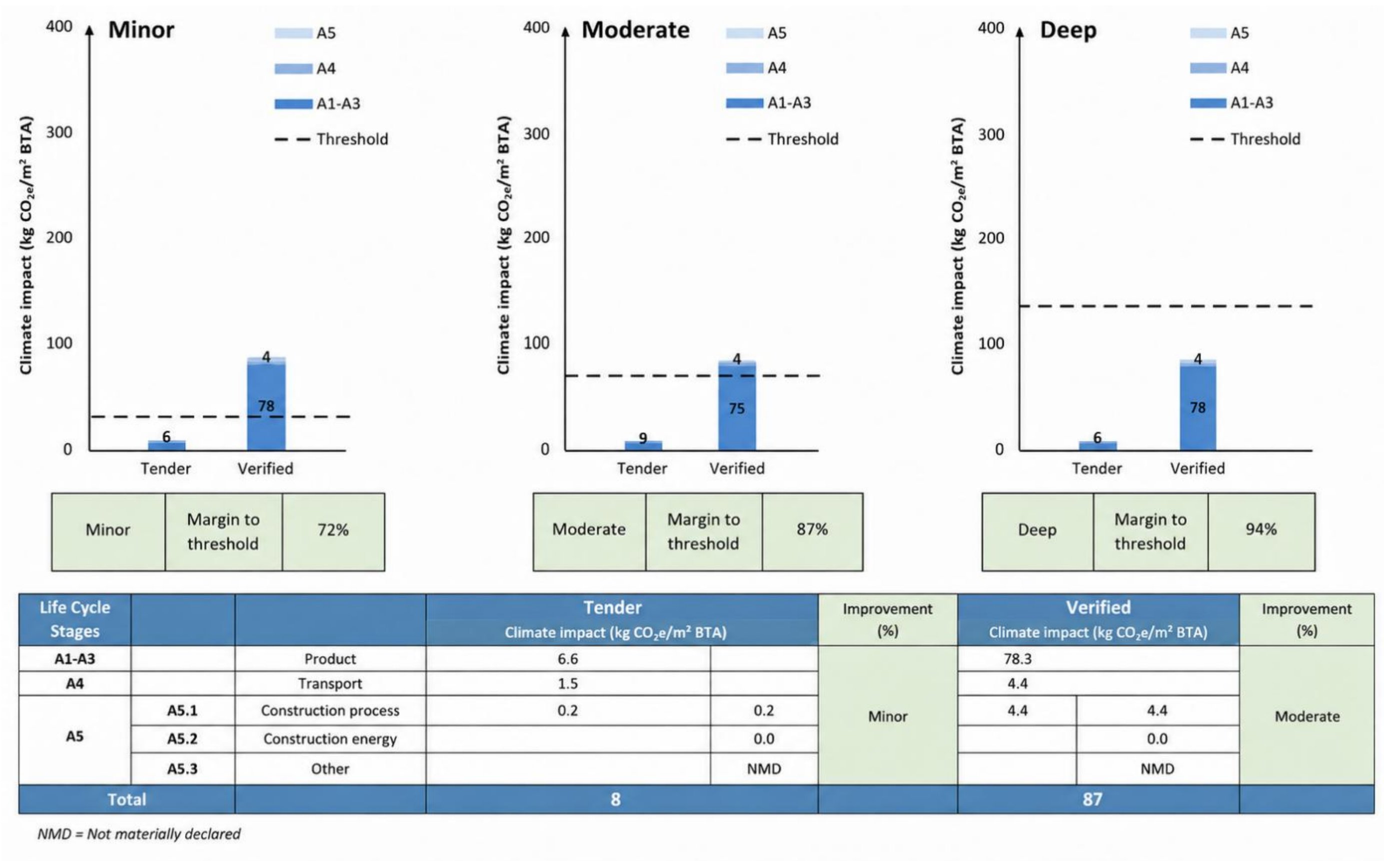


Figure 10 The figure is included only to illustrate the practical template output. The classification results for all projects are presented separately in Table 8.

3.4.3 Final cumulative impact scenario

Figure 11 shows the cumulative climate impact of the repeated tenant adaptation scenarios over a 50-year reference study period. The scenarios are compared with the current and 2035 climate thresholds for new buildings.

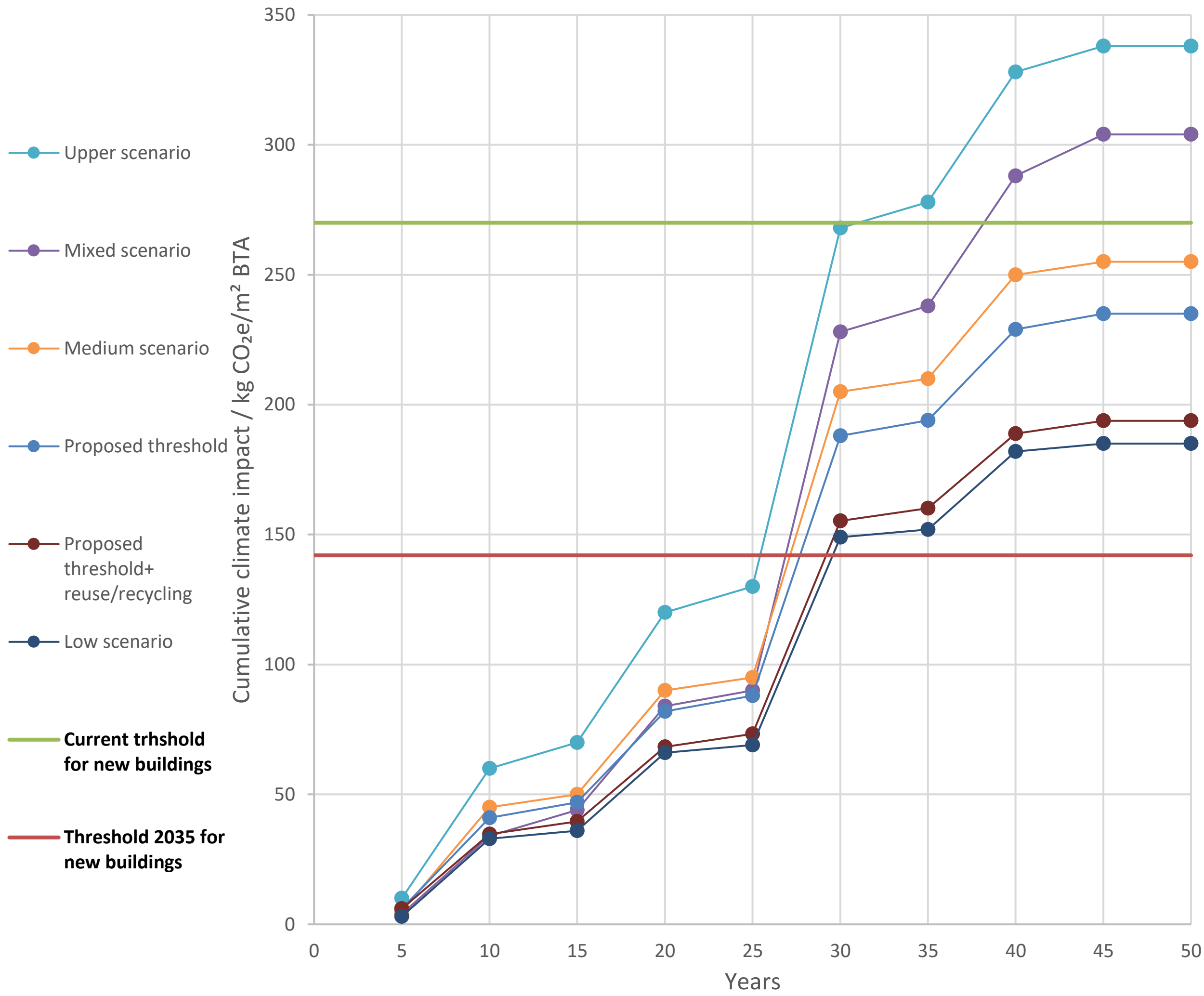


Figure 11 Cumulative climate impact of repeated tenant adaptation scenarios over time, compared with the current new construction threshold and the proposed 2035 threshold.

The results show that the cumulative impact increases stepwise as tenant adaptations are repeated over time. The high and mixed scenarios exceed the current threshold, the medium scenario approaches it by the end of the period. The low scenario and the proposed threshold scenario remain below the current threshold, but they exceed the 2035 threshold after several repeated adaptations. The proposed threshold + reuse/recycling scenario gives the lowest cumulative impact among the proposed cases but still exceeds the 2035 threshold over a longer period.

3.5 Annualised interpretation of the proposed threshold values

Table 12 presents the proposed threshold values for the three adaptation depths: light, moderate, and deep.

Table 12 Annualised interpretation of the proposed threshold values by adaptation depth.

Adaptation depth	Proposed threshold value (kg CO_2e/m^2 BTA)	Assumed interval (years) (kg CO_2e/m^2 BTA)	Annualised threshold value (kg CO_2e/m^2 BTA/year)
Light	6	5	1.2
Moderate	35	10	3.5
Deep	100	30	3.3

The table is included as an example to show how the same threshold values can be interpreted differently when different time intervals are applied. The light threshold is divided by 5 years, the moderate threshold by 10 years, and the deep threshold by 30 years.

4 Discussion

This chapter discusses the main findings of the study and explains how the results can be interpreted. The results chapter showed the climate impact, material mass intensity, adaptation depth classification, and scenario calculations. This chapter connects these results and discusses what they mean for tenant adaptations. The discussion focuses on three main points.

First, it discusses why the tenant adaptation projects differ from each other and why they should not be treated as one single type of project.

Second, it discusses the relationship between material mass intensity and climate impact, and how this can help to classify adaptations as light, moderate, or deep.

Third, it discusses the effect of repeated tenant adaptations over time, including the cumulative scenario and the annualised interpretation of the proposed thresholds.

The chapter also discusses how the use of project templates from one company may affect the results. This includes questions about assumptions, default values, and differences in data completeness between projects, and how these factors can influence the calculated values and how they are interpreted.

4.1 Variation between tenant adaptation projects

The results show that tenant adaptation projects can vary strongly from one project to another. Some projects have very low climate impact, while a few projects are close to the new construction reference projects. This variation shows that tenant adaptations should not be treated as one uniform project type. The reason for the variation is that each project includes different building element categories and different scopes of work. Some projects mainly include interior finishes or room formation, while others include installations or more material intensive elements. Another reason is the use of default values in some templates, which can affect the calculated climate impact. If all tenant adaptations are grouped together, it becomes difficult to understand if a high climate impact is caused by a deeper intervention or if the selected materials are less efficient. Therefore, the projects need to be interpreted through different adaptation depth categories. Similar findings are reported by De Wolf (2014), who shows that embodied carbon assessment depends strongly on detailed material quantity data and reliable emission factors.

4.1.1 Building element categories

The variation between projects can be explained in more detail by the building element categories included in each adaptation. The climate impact by category shows that installations have the highest average climate impact. This is followed by groundworks and energy and transport. However, ground works and energy and transport were mainly based on default values, which means that these categories should be interpreted with caution. The results show that room formation, frame, and substructure are also important contributors to the climate impact. This is reasonable because tenant adaptations often include changes to interior layouts, partitions, and technical or structural-related components.

The frequency results therefore help explain why tenant adaptations differ from new construction. The most common categories are mainly interior and technical elements; structural and envelope-related categories occur less often. This supports the interpretation that tenant adaptations are usually not whole-building interventions. However, when technical installations or heavier building elements are included, the climate impact can still increase clearly.

Another important result is the category-level CO_2e thresholds, which also followed a similar trend as the other element values. However, it should be noted that these were used as a prototype in the adapted template and should be interpreted with caution, since they were not validated as final benchmark values.

4.2 Relationship between material mass intensity and climate impact

The classification method is useful because it separates adaptation depth from climate impact. This is important because it helps to separate the effect of material quantity from the effect of material choice. Two projects can have similar material mass intensity but different climate impacts if one project uses materials with higher emission factors. This makes it possible to reduce emissions through better material selection, even when the physical scope of the adaptation remains similar.

In projects where materials were entered in detail, higher material mass intensity generally meant higher climate impact. However, the relationship becomes less clear when default values are included. Default values were based on predefined assumptions. Therefore, the material mass intensity may not fully represent the actual material use in the project. This makes the classification less certain. At the same time, projects with default values still show a general trend, where higher assumed material mass is often connected to higher climate impact. For this reason, material mass intensity can still support the interpretation of adaptation depth also with default values.

This is also supported by the classification method. The classification results in Table 8 show how the classification method separated the projects into clear groups: light, moderate, and deep adaptations. In general, projects classified as deeper adaptations also tend to have higher climate impact. This is important because the classification was based on material mass intensity, not directly on climate

4.2.1 Building element categories by mass intensity

The material-based results support the earlier category analysis. The material mass intensity by building element category shows a similar pattern to the category-based climate impact and frequency results. The same categories that are high in the climate impact results, such as room formation, installations, and structural-related categories, also appear as relevant in the mass intensity results, even though the exact order of the categories is not exactly the same. Substructure has the highest average material mass intensity, which is expected because this category usually includes heavy materials. Room formation and installations also fit the typical scope of tenant adaptations, since these categories are often adjusted together with interior changes. Overall, the category results show that tenant adaptations are mainly connected to interior and technical building elements.

4.3 Reuse and recycling scenario

The average estimated reduction was around 17%. This value shows that reuse and recycling can have a visible effect on climate impact. However, the reduction differs between projects. Some tenant adaptations have a higher potential for reuse and recycling, while others show a lower potential. This depends on which materials are included in the adaptation and how large their share is in the total A1–A3 impact. The results suggest that reuse and recycling could become more relevant if tenant adaptations are planned with reusable materials and more detailed material information. The scenario should therefore be interpreted as an indication that there is potential to reduce emissions if reuse and recycling are considered more systematically in future projects.

4.4 The impact of repeated adaptations

The cumulative scenario is one of the main findings of this study. It shows how the climate impact of tenant adaptations can add up over time when several interventions are carried out during the building use period.

As shown in Figure 11, several scenarios remain below the current new construction threshold over the analysed period. This is a positive result, since it shows that repeated tenant adaptations do not always exceed the climate impact level of initial construction over 50 years.

In the scenario results, only the high and the mixed scenario exceed the current threshold. However, this result depends strongly on the sequence of adaptations. In the cumulative scenario, a deep adaptation is included only once. If deep adaptations were repeated more often, the cumulative impact would increase strongly and would exceed the new construction threshold.

The results also show that the timing and depth of interventions affect the cumulative impact. Light and moderate adaptations have lower one-time impacts, but they can still add up when they occur several times. Deep adaptations have a higher one-time impact, but their effect depends on how often they are repeated. Therefore, a deep adaptation is not automatically negative. The proposed threshold scenario reduces the cumulative impact compared with the higher scenarios. However, the comparison with the 2035 threshold shows that further reductions would still be needed. This could include more reuse, better material choices, more detailed material planning, and avoiding unnecessary replacement of interior elements.

4.5 Annualised interpretation of proposed thresholds

The annualised interpretation of the proposed thresholds makes the results easier to compare over time, as shown in Table 12. When the threshold values are shown only as one-time impacts, deep adaptations have the highest value and light adaptations have the lowest value. However, this changes when the values are divided by the assumed time interval for each adaptation depth.

A higher one-time adaptation does not automatically mean a higher yearly impact, as mentioned earlier.

After annualisation, the difference between light, moderate, and deep adaptations becomes much smaller. The order also changes. Moderate adaptation has the highest annualised value, and deep adaptation becomes slightly lower because it is divided over a longer assumed period. Light adaptation remains the lowest, but the gap between the three adaptation depths is not very large anymore. A deep adaptation can have a high initial impact, but if it is assumed to last longer, its annualised impact can become close to or lower than a moderate adaptation. Light adaptations can become more impactful when they occur more often. Therefore, the annualised interpretation adds an important time perspective to the proposed thresholds. It shows that adaptation depth should not be judged only by the one-time climate impact, but also by the assumed period before the next intervention.

This interpretation supports the cumulative results discussed earlier, but it presents the time effect more directly. In the cumulative scenario, the impact of repeated adaptations becomes visible only after several interventions are added together. In the annualised interpretation, this effect is already reflected in the yearly value.

4.6 Interpretation of project-based and scenario-based results

To clarify how the results should be interpreted, it is useful to separate project-based information from scenario-based assumptions. The project-based information comes from the analysed templates, interviews, and patterns identified in the projects. This includes the reported material quantities, climate impact values, and the frequency of different building element categories. These results are therefore connected directly to the analysed tenant adaptation projects, although they are still affected by the quality and completeness of the submitted templates.

Other parts of the analysis were used to test possible future situations. This applies especially to the long-term adaptation sequence and the reuse sensitivity scenario. The adaptation sequence was collected through meetings. The reuse scenario was also not measured directly in the project data, but was included to explore how the climate impact could change if reuse were applied in future projects. The results from these parts should therefore be read as estimates under defined conditions, not as verified outcomes.

The depth classification is placed between these two groups. It is based on the project data, since the classification uses the reported material mass and climate impact values. However, the threshold values used to separate light, moderate, and deep adaptations were developed within this thesis. For this reason, the classification should be understood as a proposed method for this study, rather than as an established industry standard.

4.7 Future recommendations

Future research could study the relationship between climate impact and project cost in tenant adaptations. Lower emissions do not necessarily mean higher costs.

Circular approaches may also reduce material use and cost, as indicated in a Swedish office adaptation case reported by Humlegården Fastigheter (2026). More cases would be needed to test if this applies more generally.

Future research should also continue to develop and calibrate the proposed classification method and threshold values. The limits for light, moderate, and deep tenant adaptations may need to be adjusted when more project data is available. The threshold values could be higher or lower depending on the building type, service life, and material category.

This is especially important if future climate goals are considered. With the current results, it seems difficult to stay below stricter future climate targets.

Another recommendation is to improve the quality and structure of the input data. More detailed material quantities, clearer product categories, and better separation between project-specific data and default values would make the results more reliable.

The current Excel-based structure can work, but it can also create problems if the input is not detailed or consistent. A more simplified and online based model could make the process easier and more standardised. It could also help building owners and consultants to track tenant adaptations over time. In this way, repeated adaptations could be followed more clearly, and their total climate impact would not be hidden.

5 Conclusion

This thesis examined the climate impact of tenant adaptations in office buildings. The study started from the problem that tenant adaptations are often seen as smaller projects, although they can still create high CO_2 emissions. The cumulative impact of repeated tenant adaptations ranged from about 185 to 338 kg CO_2e/m^2 over the 50-year reference period. Even the lowest scenario exceeded Wihlborgs future target of 142 kg CO_2e/m^2, the highest scenarios also exceeded the current new construction threshold of 270 kg CO_2e/m^2.

Another important finding was that the interpretation changes when the emissions are annualised. One tenant adaptation is usually lower than a new construction project. However, when adaptations happen several times during a 50-year building life, the cumulative emissions can become high. For example, the proposed threshold values for adaptation depth were set at 6 kg CO_2e/m^2 for light adaptations, 35 kg CO_2e/m^2 for moderate adaptations, and 100 kg CO_2e/m^2 for deep adaptations. When these values were annualised, the results became 1.2 kg CO_2e/m^2/year for light adaptations, 3.5 kg CO_2e/m^2/year for moderate adaptations, and 3.3 kg CO_2e/m^2/year for deep adaptations. This means that the difference between adaptation depths becomes smaller when the time interval is considered. Moderate adaptations had the highest annualised impact because they occur more often than deep adaptations. At the same time, a smaller adaptation can become more extensive if it is repeated often within the same period, since the emissions add up over time.

It can be interpreted from the results that adaptation depth should not only be based on general project descriptions or cost. In practice, projects can sometimes be classified as larger or smaller depending on cost, for example if the project is above a certain cost level. However, cost does not always explain the real climate impact. A project can cost a lot but use fewer materials, while another project can cost less but include large material changes. Therefore, this thesis used material mass intensity, climate impact, and building element categories to describe the actual depth of tenant adaptations.

The study also showed that there is some potential for reuse, even with the current material flows. This potential was not large in all projects, but it still shows that reuse can be part of reducing the climate impact of tenant adaptations. If more materials are designed to be reused, removed, and exchanged more easily, the future impact of tenant adaptations could be lower.

Overall, this thesis shows that tenant adaptations need more attention in building LCA. They are not always small interventions when they are repeated over time. A clearer method based on material mass intensity, climate impact, building element categories, and service life can help compare tenant adaptations in a more transparent way. This can support better decisions, more realistic thresholds, and lower climate impact in future office adaptations.

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