FROM BUILDING TO DISTRICT: WHOLE-LIFE GLOBAL WARMING POTENTIAL OF A LOW-ENERGY RESIDENTIAL BLOCK AND SURROUNDING SITE WORKS

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Abstract

A comprehensive life-cycle assessment (LCA) was performed for a newly completed multi-family residential block and its surrounding infrastructure in Oceanhamnen, Helsingborg, to quantify total climate impacts and identify key mitigation opportunities. The study integrates dynamic energy modeling with a material-based LCA in accordance with EN 15978 (modules A–C), extending the traditional building boundary to include external, non-building components such as courtyards, access roads, and underground utility networks. The baseline concrete-dominated design results in a whole-life global warming potential (GWP) of 517 kg CO_2-eq/m² over a 50-year lifespan, of which 52% arises from embodied carbon during production. Although non-building elements contribute only about 16 kg CO_2-eq/m² (≈4% of total emissions), some, particularly service corridors and paved areas, exhibit disproportionately high carbon intensities per functional unit. The results highlight the dominant role of structural concrete in embodied emissions and show that extending the assessment boundary beyond the building elements adds only a minor but meaningful contribution to the total carbon footprint.

Keywords: life-cycle assessment, embodied carbon, non-building elements, global warming potential.

1. Introduction

According to Sweden's Climate Policy Framework (Swedish Environmental Protection Agency), the country's long-term climate goal is to have zero net greenhouse gas emissions by 2045, with negative emissions thereafter, consistent with the European Green Deal's 2050 climate-neutrality target (European Commission 2019). The building and construction sector remains one of the country's most carbon-intensive industries, accounting for approximately 37 % of total greenhouse gas emissions and nearly 40 % of raw material and primary energy consumption (Boverket 2023; IEA 2022). To address this, the Swedish Climate Declaration Act requires all new buildings to report their cradle-to-grave climate impact, with mandatory carbon-limit values proposed from 2027. These policies reflect a paradigm shift from operational energy performance toward whole-life carbon regulation. Comparable EU-level benchmarks for embodied and whole-life carbon in residential buildings have been established by Lavagna et al., providing reference values that highlight the need for consistent baseline data when extending assessments to district or site-scale contexts (Lavagna et al. 2018).

As operational energy demands decline through passive and near-zero-energy design, embodied emissions from material production and construction have become dominant, often representing over half of total GWP (Alam and Devjani 2021). Structural concrete and reinforcement steel, in particular, are consistently identified as the principal contributors across Swedish residential typologies (Malmqvist et al. 2023). Yet, while robust LCA methodologies exist for building elements, the surrounding urban infrastructure that makes a neighborhood functional, such as courtyards, pavements, roads, service tunnels, and green spaces, remains largely excluded from regulatory carbon reporting (Muszynska and Wan 2025). Recent Swedish evidence that temporal boundary extensions (A1–A5 to A1–A5+B2–B4) often have limited steering effects on design choices under proposed limit values, whereas our spatial extension surfaces overlooked emissions from site infrastructure (Barjot and Malmqvist 2024; Izaola et al. 2023).

Recent Swedish analyses have begun to address this gap by including external site components such as roads,

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courtyards, utility networks, quays, and parks in life cycle assessments. In the large-scale Klimatanalys Frihamnen study in Gothenburg, these external systems accounted for a measurable share of embodied greenhouse gas emissions during construction. While buildings and their foundations dominated the total impact (about 91% of 351,700 t CO_2e), the surrounding urban infrastructure still contributed notably: approximately 5% from service networks, 2% from roads and squares, and 2% from quays, with smaller amounts from parks and other public spaces (Tyréns AB 2021). The results show that emissions from these elements are particularly high where extensive underground reinforcement or dense utility corridors are required, highlighting the need for future carbon accounting to capture both buildings and the infrastructure that enables their use.

Despite growing recognition of their importance, on-building systems remain poorly represented in both research and practice. Current Swedish regulations focus almost exclusively on building-related components, omitting the embodied emissions of courtyards, pavements, and service installations that are integral to a building's functionality and spatial coherence. Standardized data sources and LCA frameworks for these non-building elements are still limited, leading to fragmented or simplified estimates in practice. To address this gap, the present study extends the conventional life cycle boundary to include both the building and its immediate surroundings. Its main objectives are to (1) quantify the global warming potential of the building together with its adjacent infrastructure through an extended LCA; (2) compare the relative climate impacts of building and non-building components to identify the most emission-intensive elements; and (3) explore design strategies that could reduce the overall carbon footprint and support the transition toward climate-neutral development in Sweden.

2. Method

This study processes-based life-cycle assessment (LCA) in accordance with EN 15978 to quantify the cradle-to-grave global GWP of both building and non-building components within a residential development in Helsingborg, Sweden. The methodological framework extends beyond the conventional building boundary to encompass the neighborhood's surrounding courtyards, pavements, buried utilities, and green spaces, which comprise its functional infrastructure. The primary aim is to determine the CO_2 emissions associated with these non-building elements and evaluate their relative contribution to the total project footprint. The approach integrates dynamic energy modeling with material-based LCA, combining simulated operational energy demand with embodied emissions from construction materials, transport, and end-of-life processes. Exterior works are modeled using equivalent datasets supplemented with region-specific transport and earthworks fuel data.

2.1.Case study

The case study focuses on Phase 2 of the Oceanhamnen waterfront redevelopment in Helsingborg, Sweden; one of the country's flagship districts for climate-neutral urban development. Oceanhamnen is part of the H+ regeneration program, which aims to transform former harbor and industrial land into a mixed-use, energy-efficient neighborhood connected to Helsingborg's district heating and vacuum waste systems. The selected site includes a newly completed multi-family residential block (5,762 m^2 gross floor area) and its directly adjacent 4,800 m^2 of external works, comprising courtyards, pedestrian paths, underground service tunnels, and landscaped zones.

The building complex consists of reinforced-concrete foundations, cores, and horizontal slabs with prefabricated façade panels and high-performance glazing. The external areas are designed as semi-private courtyards with permeable paving, planting beds, and integrated drainage channels. Buried utility networks for water, sewage, electricity, and telecommunications run through shared trenches beneath the access paths. This configuration provides a representative example of contemporary Swedish multi-residential construction, where compact urban form and shared infrastructure create both environmental efficiencies and additional embodied-carbon loads.

The Oceanhamnen project was chosen as a living test site because it combines measurable construction data, digital building information models, and strong municipal engagement in carbon reporting. All construction documents and as-built specifications were provided by the developer, allowing accurate quantification of material volumes for both building and non-building elements. The case therefore supports the study's broader aim: to evaluate the whole-life climate performance of a typical Swedish low-energy residential block and its immediate surroundings, and to assess how early design decisions, particularly in structural systems and site infrastructure, affect total embodied greenhouse gas emissions within a neighborhood-scale boundary.

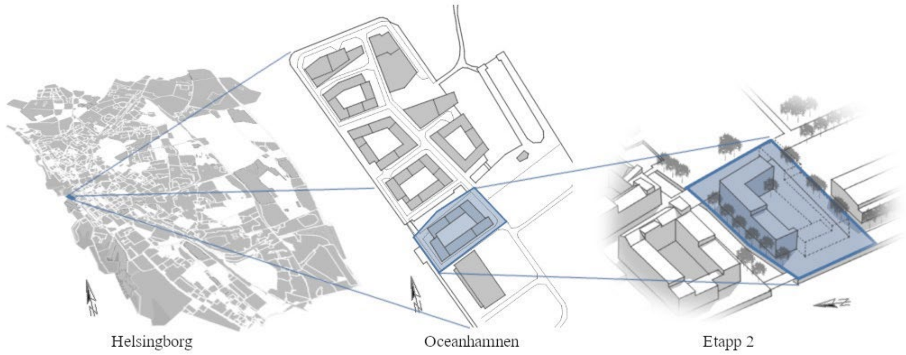

Figure 1: Stage 2 site and studied building in Oceanhamnen, Helsingborg.

2.2. Data and modelling workflow

The LCA followed a geometry-based, process-oriented workflow that links design data directly to environmental datasets for material- and construction-stage impact calculation. The workflow was developed using Rhino 7 and Grasshopper, with the Brimstone plug-in serving as the main interface for environmental data mapping. This platform allowed the extraction of material quantities from the detailed 3D geometry of the building. For the surrounding site, a detailed Excel-based inventory was developed using area and dimensional data extracted from the district planning documents and construction drawings.

For each construction layer, the geometric model was decomposed into material assemblies (foundations, slabs, façades, pavements, sub-bases, and buried utility corridors). These were parameterized by volume, area, or length, depending on their physical representation, and automatically exported to the Boverket Klimatdatabas and manufacturer-specific Environmental Product Declarations (EPDs) through Brimstone's dataset-matching system. When project-specific EPDs were unavailable, generic data from the Swedish LCA-byggdatabas.

Where project-specific EPDs were unavailable for non-building materials, functionally equivalent products from the Environdec, EPD-Denmark, and EPD-Norway databases were used as substitutes; in the few remaining cases where no Scandinavian EPD existed, European-average data were applied. For all substituted EPDs, a 25 % conservative markup was applied to the declared A1–A3 values, in line with standard Swedish practice. The A5 construction-process stage was absent from several soil-related EPDs and was therefore omitted for those materials, leading to a slight underestimation of total embodied carbon for earthwork-intensive elements. Similarly, B-stage data were missing for most non-building materials; where absent, the stage was treated as zero based on the assumption that these elements require no routine maintenance or scheduled replacement within the 50-year reference period. These omissions are acknowledged as sources of systematic underestimation and are discussed further in the Limitations section.

Transport scenarios were incorporated for all materials using regionally representative distances and modal splits between lorry and rail, in accordance with national logistics statistics. Fuel consumption associated with excavation, fill, and compaction work was calculated separately using standard diesel equipment emission factors, while soil stabilization and drainage aggregates were treated as distinct material flows due to their high mass intensity. For non-building elements, such as courtyards and utility networks, quantities were derived directly from site engineering drawings and modeled within the same Brimstone-based workflow to enable uniform aggregation and comparison with building components.

All impact data were structured following EN 15978 life-cycle modules A1–C4, capturing the cradle-to-grave stages of production, transport, construction, replacement, and end-of-life. Each dataset was normalized to the functional unit of 1 m² of gross floor area (GFA) and a reference period of 50 years, ensuring comparability between building and site components. The consolidated dataset was then exported to Excel for quality checking and final computation of Global Warming Potential (GWP 100) according to IPCC 2021 characterization factors. This workflow enables a reproducible and transparent assessment pathway that integrates both structural and infrastructural elements within a single LCA boundary, aligning with the Swedish regulatory framework for climate declarations while extending its scope to include exterior works and service infrastructure.

2.3. Life cycle assessment framework and databases

The assessment follows ISO 14040/44 and the European standard EN 15978, covering the entire cradle-to-grave system boundary (A1–C4). The assessment includes the production of construction materials (A1–A3), transport to the site (A4), on-site construction activities (A5), replacement during use (B4), and end-of-life processing (C1–C4). Module D, representing potential benefits and loads beyond the system boundary, was excluded consistent with the Swedish Klimatdeklaration methodology.

All data were harmonized to a functional unit of 1 m² of GFA consistent with national LCA reporting guidelines. Embodied emissions were quantified using IPCC 2021 characterization factors and expressed as Global Warming Potential (GWP_{100}). The primary focus was on carbon dioxide equivalent (CO_2e) emissions arising from material production, transportation, and construction processes, as these dominate the total environmental profile for both building and non-building elements. Results were aggregated by life cycle stage and component category (building, foundation, siteworks, utilities, and landscaping) to identify emission hotspots and relative contributions within the extended system boundary. The surrounding elements included in the non-building elements analysis are components such as pathways, inner courtyards, road infrastructure, green areas, and technical installations that directly support the building's use. The components were divided into main categories based on their functions and structural characteristics, and then further subdivided into smaller groups according to their location within the site (Figure 2).

For the non-building elements, several key assumptions were applied consistently throughout the assessment. (B6) were excluded because no metered data were available for these elements. Where A5 data for earthworks or soil-related materials were missing in EPDs, these stages were omitted, resulting in a slight underestimation of embodied carbon. In cases where project-specific EPDs were not available, functionally equivalent products from Scandinavian or European databases were used, with a conservative 25 % markup applied to A1–A3 values to reduce the risk of underestimation. These assumptions provide a consistent framework for evaluating non-building elements while acknowledging inherent sources of uncertainty.

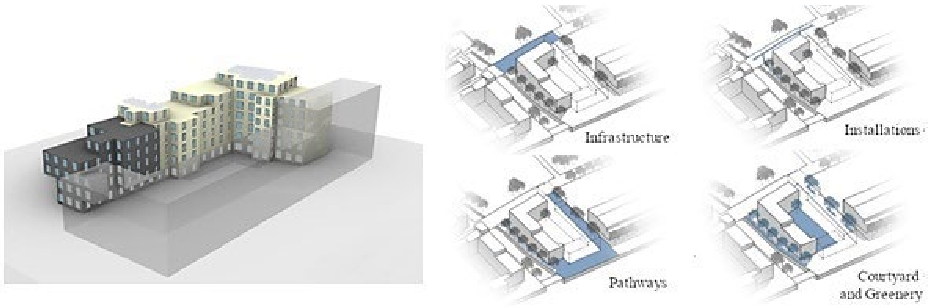

Figure 2: 2D 3D geometry to the left and division of non-building elements to the right.

3. Results

3.1. Building elements

Figure 3 summarizes the whole-life carbon results for the analyzed building, structured by EN 15978 modules. The production stage (A1–A3) is the largest contributor at 237 kg CO_2-eq/m², followed by operational energy use (B6) at 158 kg CO_2-eq/m². Electricity exported from the photovoltaic (PV) system to the grid (1.1 kWh/m²·yr) provides a net credit of −2 kg CO_2-eq/m², calculated with the regional, supply-weighted grid emission factor. Including construction (A4–A5), in-use non-energy modules (B2–B5), and end-of-life (C1–C4), the total whole-life GWP amounts to 453 kg CO_2-eq/m² of gross floor area.

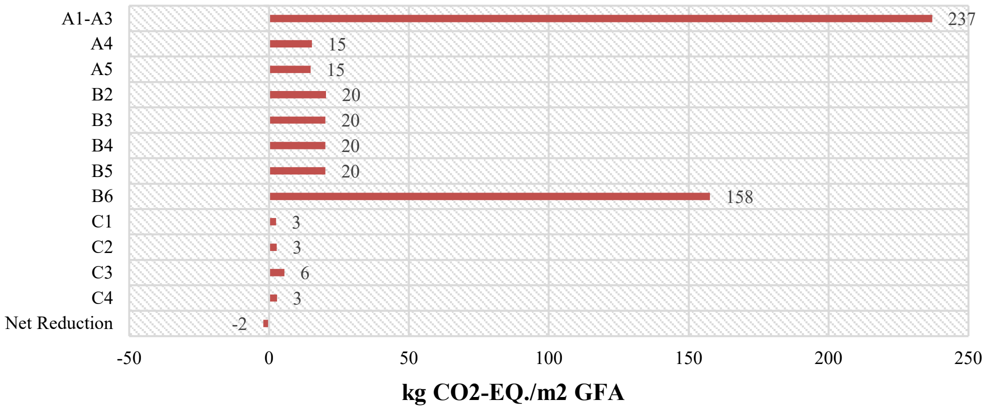

Figure 3: LCA results for the baseline building. Total whole-life GWP

All the building-relevant components were grouped into six categories: façade, basement, foundation, structure, slabs and others, as shown in Figure 3.2. In total, the building's whole lifespan emissions accounted for 363 kg CO2-eq./m2.

The highest A-stage impact originated from the horizontal structure (slabs), which contained the largest quantities of concrete and rebar. These contributed 115 kg CO_2-eq/m², of which 111 kg CO_2-eq/m² occurred during stage A. In this category, approximately 98 % of emissions were associated with concrete and 2 % with reinforcement steel. The shear-wall and external supporting structures followed, together accounting for 77 kg CO_2-eq/m², with nearly all (≈76 kg CO_2-eq/m²) arising from stage A.

The façade exhibited the largest total whole-life impact, 129 kg CO_2-eq/m², of which modules B2–B5 accounted for 80 kg CO_2-eq/m². This high contribution is primarily due to many façade materials, such as weather barriers, insulation, and glazing, being sourced from the BM database, which applies conservative assumptions for life-cycle stages B2–B5. Consequently, the estimated maintenance and replacement impacts are likely overestimated relative to real-world conditions, where many façade materials are not replaced during a 50-year lifespan.

The C-stage (end-of-life) impact was negligible across all categories, partly because this stage is not included in some EPD system boundaries, and partly because many materials (e.g., reinforced concrete) require limited energy for deconstruction. Most concrete structures are mechanically demolished, producing minimal additional emissions.

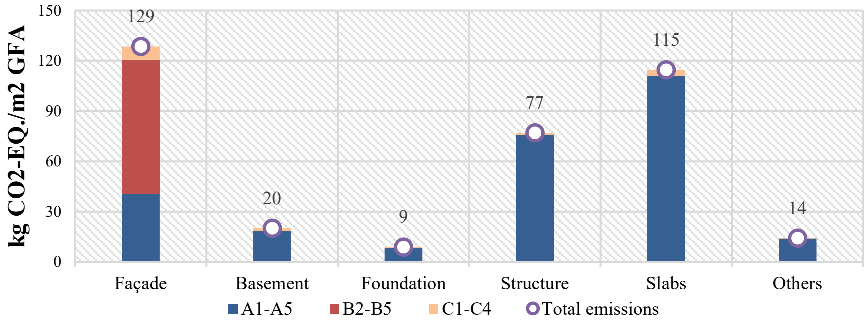

Figure 4. Carbon emissions across categories.

To verify model reliability, Figure 5 compares the A-stage (A1–A3) results with the official project Climate Report. The modelled subset of materials,when aligned to the same boundary, captures approximately 90 % of the reported A-stage impact. Extending the boundary to include foundations, basement, and integrated PV increases the modelled A-stage total by 10–15 %, explaining the small positive deviation from the report. This consistency demonstrates that boundary selection, rather than data or calculation error, accounts for the observed difference.

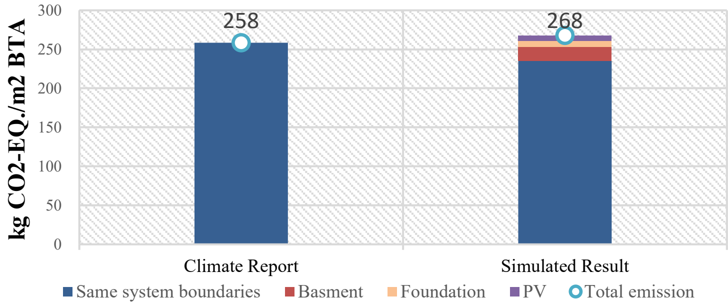

Figure 5. Comparison between the Climate Report and the modelled results.

3.2. Non-building elements

The results presented in this section are based on the total quantities of materials used within the analysed Etapp 2 building site. All calculated environmental impacts are expressed in kilograms of CO_2 equivalent (kg CO_2 eq). Presenting the results in this way provides insight into the emission ratios and relative contributions specific to the project's context.

Figure 6 shows the percentage distribution of GWP values among the non-building element categories. Pathways contribute the largest share, about 34 percent of the overall carbon footprint of non-building materials, while Installations represent the smallest share at 16 percent. Figure 7 presents the total GWP values for each category divided into life-cycle stages A (production), B (use and maintenance), and C (end of life). Stage A accounts for the majority of emissions across all categories. Stage B is almost negligible, although a noticeable negative value appears within the Courtyard and Greenery category, reflecting modelled carbon storage or offset effects from vegetation.

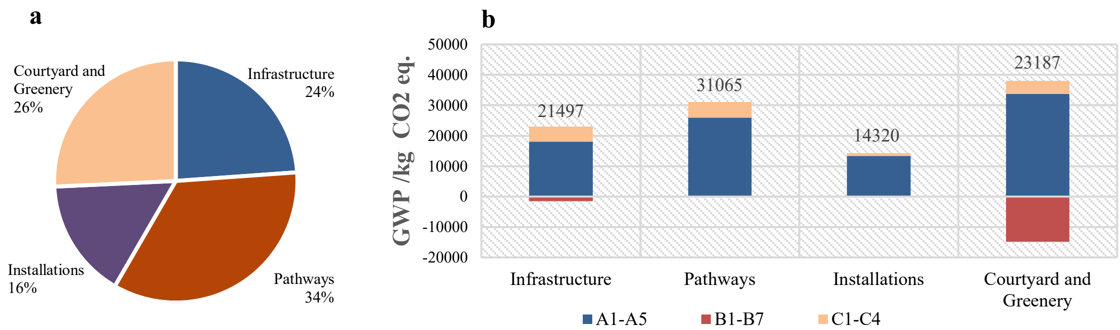

Figure 6. (a) Percentage distribution of non-building element categories within the building complex; (b) total GWP of non-building element categories by life-cycle stage (A–C).

At the subcategory level, the Main Road structure within the infrastructure category shows the highest impact at 9,856 kg CO_2 eq. Pathways remain the most impactful element across the site overall, with 31,065 kg CO_2 eq. After Greenery was defined as a separate category, the Courtyard values now represent only the materials used specifically within the complex's inner courtyard. The detailed GWP distribution, carbon density, and normalized results per GFA, as well as transport and earthwork emissions, are summarized in Table 7.

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Category	Stage A1–A5 (kg CO_2)	Stage B1–B7 (kg CO_2)	Stage C1–C4 (kg CO_2)	Total GWP (kg CO_2)	Total GWP Per GFA ($kgCO_2eq/m^2$)
Infrastructure	18058	-1475	4913	21496	3.72
Pathways	25985	0	5081	31066	5.38
Courtyard	33692	-14855	4351	23188	4.02
Installations	13356	0	964	14320	2.48

3.3. Building vs non-building elements

The results show that the building structure accounts for the largest share of total emissions, followed by operational energy use (B6). At the same time, non-building elements contribute a smaller share, around 3.41%

of the total GWP, mainly from pathways and courtyards. Earthworks represent the least impact. This highlights that embodied emissions in structural materials remain the main driver of whole-life carbon, with non-building elements adding a modest but measurable contribution to the overall footprint.

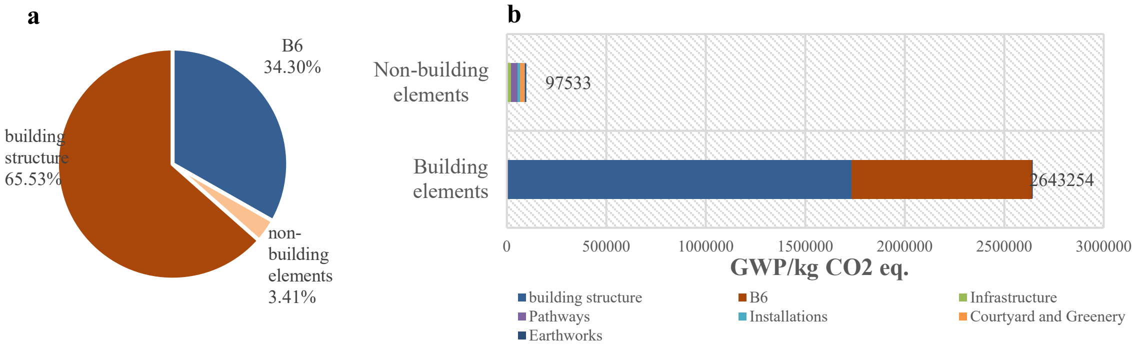

Figure 7. (a) Total GWP within the building complex by main categories. (b) Percentage distribution of GWP for the original building scenario.

4. Conclusion

This study extends the traditional building-focused life cycle assessment to include both the residential structure and its surrounding site works, providing a comprehensive view of whole-life GWP at the district scale. The results confirm that structural concrete is the main source of embodied emissions, with production processes in stages A1–A3 dominating the total carbon footprint. Operational energy use in stage B6 also represents a significant share, while non-building elements such as pathways, courtyards, installations, and earthworks contribute a smaller yet meaningful portion of about 3.41 % of the total GWP, equivalent to approximately 16.9 kg CO_2-eq per m² of GFA or 107.3 kg CO_2-eq per m² of building footprint. Among these, pathways exhibit the highest carbon intensity due to the extensive use of concrete and sub-base materials.

Although the 3.41 % share of non-building elements may appear modest compared with the building's embodied emissions, it becomes considerable when scaled up to the neighborhood or city level, where extensive external works multiply the total area of infrastructure. This emphasizes that surrounding courtyards, pavements, and buried utilities, though often excluded from regulatory carbon declarations, represent a non-negligible contribution to the overall environmental burden of urban development.

Furthermore, by substituting conventional reinforced-concrete systems with eco-friendly or low-carbon materials can reduce the building's GWP. Under such alternative design scenarios, the relative share of non-building elements within the total carbon footprint would increase proportionally, highlighting the need for coordinated carbon-reduction strategies that address both building and site infrastructure.

Overall, the research underscores the importance of integrated and extended carbon accounting that encompasses the entire development boundary. Expanding national and European regulatory frameworks to include non-building elements, together with early-stage design measures promoting material efficiency and circular construction, will be essential for achieving Sweden's and the EU's long-term climate-neutrality targets.

Limitations and uncertainty. The assessment of non-building elements carries several sources of uncertainty. Material quantities and properties for pathways, courtyards, and buried utilities were derived from construction drawings and external databases, but some components lacked project-specific EPDs. In these cases, functionally equivalent Scandinavian or European-average EPDs were used, with a conservative 25 % markup applied to A1–A3 stages to reduce the risk of underestimation.

Stage B (replacement/maintenance) for non-building elements was assumed to be zero where no lifespan data were available, and stage A5 for earthwork-related materials was omitted when construction EPDs were incomplete. These assumptions introduce uncertainty in absolute GWP values, but the relative contribution of non-building elements to the total carbon footprint is expected to be robust.

Two sensitivity checks were conducted specifically for non-building elements: (i) alternative transport scenarios, including realistic rail+lorry and lorry-only scenarios were tested to bound emissions from material delivery, and (ii) different material substitutions were examined to verify the influence of EPD choice on total GWP. These analyses confirm that pathways and courtyards remain the most emission-intensive non-building components under reasonable variations in modelling assumptions.

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