Towards urban LCA: examining densification alternatives for a residential neighbourhood

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RESEARCH

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ABSTRACT

This paper explores the environmental impacts of retaining or replacing buildings by extending the consequential replacement framework (CRF) for life-cycle assessment (LCA) from individual buildings towards the urban scale. It addresses a gap in previous studies by examining the broader consequences of building-level retention or replacement decisions in the built environment, namely greenhouse gas (GHG) emissions from associated infrastructure construction. The case study, which is located in Finland, investigates alternative ways to densify a growing city, some of which can be achieved within the urban structure, while others require greenfield construction elsewhere in the city. The results reveal that refurbishing and extending already existing buildings is worthwhile in terms of GHG emissions, even if some of the additional floor area targeted in densification were to be built on a greenfield site. After 50 years, the accumulated GHG emissions of scenarios that develop existing buildings are 0.2–12% less than those from replacement scenarios, depending on whether the targeted densification is minor or major and the amount of infrastructure construction involved. This is primarily due to the 11–35% smaller upfront embodied GHG emissions of refurbishment compared with new construction—which 50 years do not offset.

POLICY RELEVANCE

This paper reinforces the notion from previous research that developing the existing building stock holds major emission-savings potential, even more so than replacement with energy-efficient new build. It highlights the potential contribution of existing building stocks in low-emission city development, even in growing city contexts. The case study results challenge the common belief in urban planning that if replacement involves densification, it must be a more low-emission alternative than retention, and conversely, if retention leads to greenfield construction, it must be higher in emissions

KEYWORDS:
consequential replacement framework; demolition; embodied emissions; greenfield construction; infill construction; life-cycle assessment; renovation; urban densification; urban planning

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than replacement. Low-emission urban planning should base its conclusions on urban LCA. This paper introduces an infrastructure-extended CRF that accounts for building retention and replacement scenarios, ensuring methodological robustness. The approach is essential for policymakers to base their decisions on evidence and prioritise low-emission development alternatives. Which policymakers hold power over such decisions and which instruments are suitable to pursue these goals depend on the context.

1. INTRODUCTION

The European Union (EU) is committed to decrease its net greenhouse gas (GHG) emissions significantly, by at least 55% by 2030 from the 1990 level (European Council 2023). Correspondingly, several EU member states have set ambitious targets to reduce GHG emissions and achieve carbon neutrality, as can be found in the Climate Change Laws database by Grantham Research Institute (2023). Denmark aims to reduce its emissions by 70% by 2030. The Netherlands targets a 49% reduction by 2030 and 95% by 2050. Sweden plans to cut emissions by 2040 by at least 75% from sectors covered by the EU's Effort Sharing Regulation, which includes building construction and operation. Finland—the location of the current paper's case study—aims for a reduction of 80% by 2050 (Grantham Research Institute 2023).

Buildings and the construction industry are significant contributors to emissions, so the sector's effort is necessary in this endeavour. In Finland, building heating alone makes up about one-third of the country's total emissions (MoE 2022). So far, efforts to cut building-related emissions have mainly focused on constructing more energy-efficient buildings. As elsewhere (*e.g.* Power 2008), demolishing old, allegedly 'inefficient' buildings has been seen as a climate action (MoE 2020). However, despite increased new construction, building-borne household energy consumption has not notably decreased in the EU, and it has even risen in Finland. This trend has been driven by the growing number of homes and their larger size, as well as an increased stock of electrical equipment (Odyssee-Mure 2021a, 2021b). Simultaneously, the embodied emissions—those related to construction materials and works—resulting from building replacement (*i.e.* demolition and new construction) have often been overlooked (Kangas *et al.* 2020). To prevent further adverse policy consequences, there is an urgent need for a more comprehensive understanding of building-related GHG emissions.

Life-cycle assessment (LCA) methods have been customised for the building sector (CEN 2011). At present, however, most studies delve into the building scale only (Seyedabadi & Eicker 2023). Building-LCA methods typically focus on new construction and have limited applicability to refurbishment (Kuittinen 2019), though refurbishment LCAs have improved and are discussed in detail in, for example, the International Energy Agency's (IEA) *EBC Annex 72* (2019). Nevertheless, GHG emissions of refurbishment have been mainly studied as a phenomenon separate from new construction, often by comparing specific repair solutions with one another (Vilches *et al.* 2017). Moreover, LCA on the wider urban scale is still only emerging from the 'sister' discipline of material flow analysis (MFA) (Goldstein & Rasmussen 2018). This wider scale includes the impact of replacing existing buildings with new ones—the topic of interest of the current paper.

Consequential life-cycle assessment (CLCA) focuses on understanding the environmental impacts that are propagated in a system, such as the built environment, as a consequence of a decision (Institute for Environment and Sustainability, Joint Research Centre, European Commission 2010). Its derivative, consequential replacement life-cycle assessment (CRLCA), aids decision-making in situations that concern retaining or replacing an existing product, such as a building. A dedicated methodological frame, the consequential replacement framework (CRF) for buildings, has been introduced for such studies on the building scale (Huuhka *et al.* 2023). The purpose of the current paper is to extend the CRF towards the wider scale of the built environment by including the impact of urban infrastructure, such as street and service network construction. This study asks whether, as an urban development strategy, it is more climate-friendly to develop existing buildings or to demolish and replace them with new ones. In doing so, the study contributes building blocks to the emerging field of urban LCA.

Currently, few peer-reviewed CRF studies exist even on the building level, let alone the wider urban scale. In a review, Salmio (2022) identified 19 publications, only seven of which were peer-reviewed articles. Table 1 lists these publications, along with additional papers identified. Apart for few exceptions (Dong *et al.* 2005; Hawkins & Mumovic 2014), all reviewed studies conclude that refurbishment is more environmentally friendly than new construction, regardless of the building type or location. Meijer & Kara (2012) found that refurbishment is preferable only if heating energy consumption is similar to a new building. However, replacement is the better option if new construction has clearly lower operational GHG emissions and a substantially longer life expectancy.

Although both replacement and refurbishment may have consequences beyond plot borders, very few studies consider this. Only two papers compare entire residential areas: Säynäjoki *et al.* (2012) analysed a neighbourhood with detached houses, while Heinonen *et al.* (2011) assessed a residential area containing both detached houses and blocks of flats. These articles include the impacts of not only buildings but also infrastructure. Nevertheless, they reached the same conclusions as most of the building-level studies: refurbishment is more environmentally friendly than replacement.

Table 1: Review of peer-reviewed consequential replacement framework (CRF) publications: scope and results.

AUTHOR(S)	YEAR	COUNTRY	BUILDING TYPE	SCOPE	CONCLUSION, MORE CLIMATE FRIENDLY ALTERNATIVE	
					REPLACEMENT	REFURBISHMENT
Erlandsson & Levin	2004	Sweden	Blocks of flats	Building		×
Dong *et al.*	2005	Canada	Detached houses	Building	×	
Power	2008	UK	Blocks of flats	Building		×
Heinonen *et al.*	2011	Finland	Blocks of flats	Neighbourhood		×
Säynäjoki *et al.*	2012	Finland	Detached houses	Neighbourhood		×
Horváth & Szalay	2012	Hungary	Blocks of flats	Building		×
Meijer & Kara	2012	Netherlands	Blocks of flats	Building	×	×
Ding	2013	China	Blocks of flats, detached houses	Flat		×
Hawkins & Mumovic	2014	UK	University buildings	Building	×	
Gaspar & Santos	2015	Portugal	Detached houses	Building		×
Weiler *et al.*	2017	Germany	Blocks of flats	Building		×
Hu	2017	US	Opera houses	Building		×
Zhang & Wang	2017	China	Blocks of flats	Building		×
Berg & Fuglseth	2018	Norway	Detached houses	Building		×
Marique & Rossi	2018	Belgium	Office buildings	Building (no use stage)		×
Hasik *et al.*	2019	US	Office buildings	Building (only materials)		×
Ferriss	2021	US	Dormitories	Building		×
Schwartz *et al.*	2022	UK	Detached houses	Building		×
Huuhka *et al.*	2023	Finland	School buildings	Building		×
Zimmermann *et al.*	2023	Finland, Denmark, Sweden	Blocks of flats	Building		×
Moisio *et al.*	2024	Finland	School buildings	Building		×

In practice, however, urban (re)development scenarios can take up much more nuanced forms than retaining or replacing either singular buildings or whole neighbourhoods. Depending on the aims and context of the (re)development, relevant scenarios may include a combination of different strategies, such as refurbishment of existing buildings with or without extension, building replacement with or without densification, infill building and urban expansion (greenfield construction). Therefore, the current paper first introduces an extended CRF that will help researchers to consider such strategies and branch out from the building level towards the wider urban level. Second, it uses a Finnish case study plot with blocks of flats to demonstrate its use. The starting point of the case study is the aim to densify the urban structure. Alternative urban development scenarios that fulfil this aim are devised for the case plot and beyond, and the resulting GHG emissions are compared.

2. METHOD

2.1 CRF FOR THE BUILT ENVIRONMENT

Huuhka *et al.* (2023) presented the CRF as a tool to harmonise methodologies of studies comparing refurbishment and replacement of buildings. The basics of the CRF are explained in their original article. It covers the processes that are expected to change because of a building owner's decision to retain or replace a building. These include, for example, the demolition of the existing building in the replacement scenario, but not the building's original construction or previous use stages before decision-making.

The current article demonstrates the extension of the CRF's scope from the exclusive scale of a building towards that of the wider built environment. This happens by examining densification, which introduces more complex urban development scenarios than a simple building replacement. In each investigated scenario, system boundaries are set by the effects the scenario propagates, whether within the plot where the development began or elsewhere in the urban structure. This calls for incorporating, in addition to buildings' emissions, emissions related to associated earthworks and infrastructure construction. Any scenario emissions are calculated as sums of their parts. The extended CRF also lends itself to including further emission sources, such as residents' mobility or diminishing carbon sinks due to felled trees/woods, even if they are excluded from this paper's case study.

To provide a framework suitable for a variety of situations, Figure 1 shows the scopes for four distinct urban development strategies. Three of these, *i.e.* refurbishment (including extension, if any), replacement and infill, are located within existing urban infrastructure, while greenfield construction requires laying down new infrastructure. Both infill and greenfield construction, however, take a new plot into use, resulting in earthworks. Some earthworks also relate to the redevelopment of the plot if existing buildings are replaced. Next, the combination of these strategies into fully fledged scenarios is discussed in the context of the paper's case study.

2.2 CASE STUDY SCENARIOS, MATERIALS AND METHODS

The case study is located in the City of Vantaa, Finland. It starts with a plot (plot 1) containing two 1970s' rental block of flats (of three and five storeys). Since the city is growing rapidly, the aim is to consider alternatives to achieve urban densification.

2.2.1 Compared scenarios

Four alternative scenarios (S1–S4) are examined. They lend themselves to two separate comparisons, one for moderate densification (S1 versus S2) and the other for major densification (S3 versus S4), as shown in Table 2 and elaborated more below.

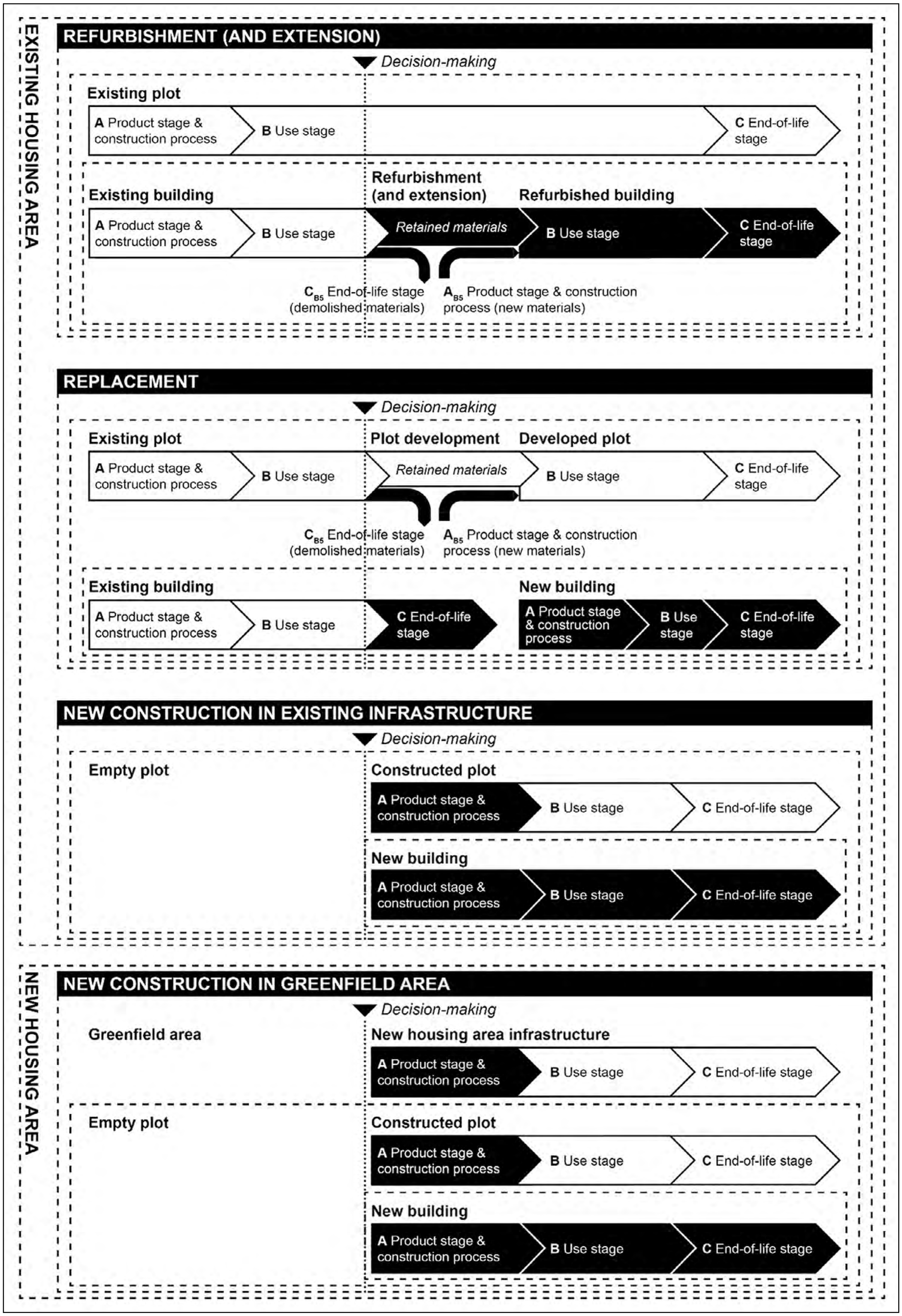

Figure 1: Infrastructure-extended consequential replacement framework (CRF) scopes of four distinct urban (re)development strategies that can be combined into urban (re)development scenarios.

Note: Life-cycle assessment (LCA) modules are from standard EN 15643:2021 (CEN 2021). Only modules occurring temporally after decision-making are incorporated. The paper's case study includes the modules shown in black.

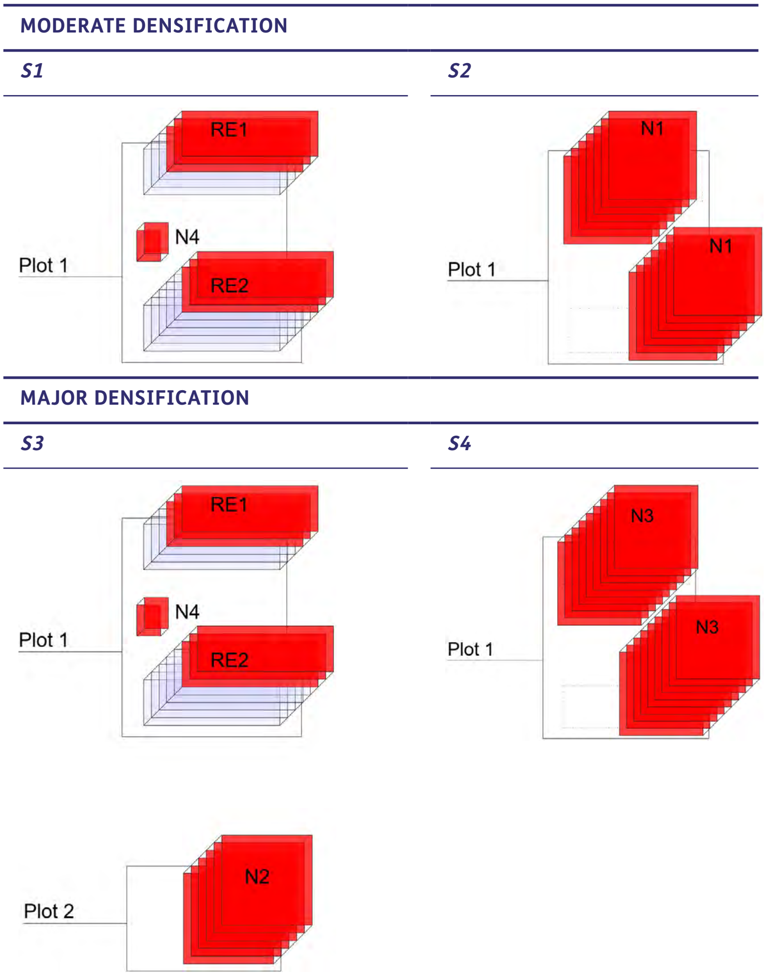

Table 2: Compared scenarios S1 versus S2 and S3 versus S4.

Note: For more detailed information and explanations of the scenarios, see Tables 3 and 4.

Comparison 1: Moderate densification

First, two alternative scenarios (S1 and S2) to moderate densification of plot 1 are examined. S1 is a retentive scenario that refurbishes the existing buildings and extends both with two storeys (RE1 and RE2). The resulting plot efficiency (gross floor area per plot area) is 2.1, which roughly equals the average in Vantaa (City of Vantaa 2019a, 2019b). The net heated area of S1 is 5600 m^2. Due to the extension, the existing civil defence shelter, which is mandatory for blocks of flats in Finland, becomes too small for the increased number of residents. Therefore, a new civil defence shelter (N4) must be built on-site to complement the existing shelter. Because N4 is an unheated structure that can be used in peace time for, for example, bicycle storage, it is excluded from the net heated area. However, its embodied, operational and end-of-life emissions are included.

The alternative, S2, is a replacement scenario that demolishes the existing buildings and erects two new buildings (N1) on plot 1. The net heated area is the same as in S1: 5600 m^2. As per the CRF, the emissions from demolishing the existing buildings (module C) are included. However, the plot's clearance is included only partially due to data availability. Demolition of building service systems on the plot is included, but the demolition of site materials is excluded due to lack of data.

The emissions from rebuilding the plot (pile-driving and site surface structures, *e.g.* asphalt pavements) are also included. Table 3 summarises both scenarios.

	S1			S2	
Plot area (m²)	2,859			2,859	
Total net heated area (m²)	5,600			5,600	
Demolition, net heated area (m²)	0			3,552	
Building and construction measures	**RE1** Refurbishment and extension, smaller building	**RE2** Refurbishment and extension, larger building	**N4** New civil defence shelter	**N1** New medium-sized block of flats	**N1** New medium-sized block of flats
Building net heated area (m²)	2,341	3,259	46[a]	2,800	2,800
Floors (*n*)	5	7	1	6	6

Table 3: Details of scenarios S1 and S2.

Note: [a]Net area, unheated.

Comparison 2: Major densification

The second comparison examines a situation where moderate densification is insufficient to meet a city's targets. The possibility to add storeys to existing buildings is limited, first, by the buildings' structural strength and construction materials used for the new storeys (heavy, *e.g.* concrete/bricks, or lighter, *e.g.* wood/steel), and second, it is influenced by the plot's size, shape and existing building placement. Starting from the same plot 1, two alternative scenarios are examined: S3 (retentive redevelopment) and S4 (replacement), both targeting a net heated area of 8018 m². This target was defined based on recently completed high-density construction near plot 1.

For the retentive scenario S3, the structural capacity of buildings on plot 1 to support additional stories was assessed. The maximum upper limit was determined to be two storeys, *i.e.* as in S1. Due to the lack of space to add new residential buildings on plot 1, S3 propagates (in addition to the measures implemented in S1) the construction of a new building (N2) on previously unbuilt land (plot 2) to achieve the targeted increase in floor area. Both plots 1 and 2 have a plot efficiency of 2.1. S3 is divided to three sub-scenarios S3.1–S3.3, depending on the location of plot 2. S3.1 is located on the edge of the neighbourhood along an existing street, thus utilising existing infrastructure. In S3.2 and S3.3, plot 2 is located on a separate, newly established housing area, founded on a greenfield site. They incorporate the upfront embodied emissions of the new neighbourhood's infrastructure, but differ in how the emissions are allocated. S3.2 uses building floor area, while S3.3 employs an allocation method detailed below, where buildings with higher plot efficiency bear fewer emissions per heated net area.

The replacement-based scenario S4 is comparable with S2, but with a higher density. Plot 1 is rebuilt with two new eight-storey buildings (N3), resulting in a plot efficiency of 3.0. Table 4 summarises both scenarios.

	S3				S4	
Plot area (m²) (plot 1/plot 2)	2,859/1,235				2,859/–	
Total net heated area (m²)	8,018				8,018	
Demolition, net heated area (m²)	0				3,552	
Building and construction measures	**RE1** Refurbishment and extension, smaller building	**RE2** Refurbishment and extension, larger building	**N2** New small block of flats	**N4** New civil defence shelter	**N3** New large block of flats	**N3** New large block of flats
Building net heated area (m²)	2,341	3,259	2,418	46[a]	4,009	4,009
Floors (*n*)	5	7	5	1	8	8

Table 4: Details of scenarios S3 and S4.

Note: [a]Net area, unheated.

2.2.2 Case buildings

Two case study buildings are used to form the scenario buildings. The retentive scenarios S1 and S3 base the buildings RE1 and RE2 on a typical 1970s' block of flats. The replacement scenarios S2 and S4 base the buildings N1 and N3 on a typical contemporary block of flats. In the retentive scenario S3, the building N2 on plot 2 is also based on the same case building, the volume of which is adapted for each situation. Only the civil defence shelter N4 was designed anew for S1 and S3.

Refurbished and extended blocks of flats (RE1 and RE2)

The starting point for RE1 and RE2 is a 1970s' block of flats, located on plot 1 and representing the architecture of its time, both structurally and spatially. Each residential storey consists of two staircase units, each with three flats (Figure 2). The building is made of prefabricated concrete, with 'sandwich' exterior wall panels and hollow-core slab floors. The main structure types are presented in more detail in File 1 in the supplemental data online.

Figure 2: Floor plan of the 1970s' case building with new elevator shafts (RE1 and RE2).

The building was adapted to model both buildings to be refurbished and extended on plot 1 (RE1 and RE2) by adjusting the number of floors. To streamline the process, the same building information model (BIM) of the three-storey building was utilised for the five-storey building by incorporating additional floors, despite minor differences in the actual building plans.

The refurbishment was designed in accordance with typical and proven repair methods (JUKO, Julkisivuyhdistys ry n.d.; Weijo *et al.* 2019) and Finnish building regulations (MoE 2013). The facade renovation involves adding extra insulation to comply with energy regulations (MoE 2013) and a rendered surface. The building services are renewed and mechanical ventilation with heat recovery is added. Elevators are retrofitted to improve accessibility. Bathrooms and other interior surfaces are replaced, and balconies are repaired and glazed. All windows and doors are replaced.

Both existing buildings are extended by adding two similar storeys (Figure 3) on each building. Each additional storey entails 12 new flats. Existing buildings' roofs are removed, and steel beams added on top of existing roof slabs to distribute loads from additional storeys to load-bearing walls below. Existing pile foundations were evaluated through calculations using current drawings and estimated to withstand the increased loads without additional strengthening. External wall assemblies, intermediate floors and roof trusses of the extensions are all made of timber. Ventilation machine rooms are added on the roofs and the new elevator shafts are implemented as bays protruding from the building, founded on concrete piles. The elevator shafts are made of steel, on new concrete foundations with piling. The extensions' facades are clad with fibre cement sheets.

Figure 3: Floor plan of the extension in RE1 and RE2.

New blocks of flats (N1–N3)

The new buildings N1–N3 are based on a contemporary block of flats, built in 2018 and located near plot 1. Its structural types are typical: walls are precast concrete panels, and the roof and floors are hollow-core slabs. The main structure types are presented in File 1 in the supplemental data online.

The original building (N2) is a five-storey block with a net heated area of 2418 m^2 (Figure 4). Three sizes of new construction were created based on it. Construction materials for N1 and N3 were determined based on N2 as follows. First, duplicates of a recurring middle storey were added to reach the closest approximation of the targeted floor area, resulting in six storeys for N1 and eight storeys for N3. This allowed the building footprints to be retained and thus the distribution of materials between various building parts to be realistic. Second, the material amounts for the above approximation, derived from Kaasalainen *et al.* (2023), were scaled proportionally to the ratio between approximated and targeted floor area to reach the final material amounts. N1–N3 are founded on concrete piles, the number of which was estimated based on new construction projects.

Figure 4: Floor plan of the typical new construction case building.

The construction of the plot's curtilage is included in all scenarios. In scenarios S1 and S3, 10% of the paved areas of plot 1 will be renewed. In scenario S3, plot 2 will be fully constructed, similar to plot 1 in scenarios S2 and S4. This includes both the pavements and their structural layers. It is assumed that 20% of the plot´s curtilage will be lawn and 80% asphalt. Structural layers of the trafficked areas are based on RT 89-11002 (Rakennustieto 2010). For material types, quantities and wastage, see File 2 in the supplemental data online.

New civil defence shelter (N4)

The new civil defence shelter (N4) was added to fulfil the requirements in the Decree on Civil Defence Shelters (MoI 2011). N4 was designed as a simple unheated single-storey shelter with an area that meets the building regulations: 2% of the added floor area (MoI 2011). The shelter is founded on concrete piles.

2.2.3 New housing area infrastructure

Sub-scenarios S3.2 and S3.3 involve the development of a new housing area on a greenfield site, where plot 2 will be situated. This includes infrastructure construction and associated embodied GHG emissions. The new neighbourhood consists of plots for detached houses, row-houses and block of flats. An urban plan of a new residential area (City of Tampere 2019) was used to define the dimensions of plots, streets, sewerage, water and energy supply. The area includes three types of streets: access roads, local distributor roads, and pedestrian and bicycle ways. The water supply network includes water pipes, sewers and stormwater pipes. The network was not dimensioned, but diameters and materials were founded on the number of dwellings and commonly used pipe types in the Helsinki Metropolitan area. The heating network consists of district heating pipelines; however, the electricity network is excluded due to insufficient data availability. Pipeline trenches are assumed to align with streets, making their lengths equivalent to the streets. The length of communication pipes is assumed to be half the width of streets. Rainwater wells and manholes were added to each branch point or every 50–60 m. Trench depths are based on minimum gradients. Each branch was individually modelled, using an average trench depth. Structural layers of streets, and measures and materials of pipeline trenches, were based on General Quality Requirements for Infrastructure Construction (Rakennustieto 2023) and are presented in File 2 in the supplemental data online.

A constant 10-m clay layer is assumed to exist in the area. For ground improvement under streets and pipeline trenches, the column stabilisation method, one of the most used methods in Finland (Kivi 2021), was selected. In it, a mixture of lime and cement is mixed with the soil to form columns. The stabilised columns have a diameter of 0.7 m and are placed at 1.3-m intervals under street structures. Column length varies depending on street type. On both sides of a pipeline trench there are inclined unified walls consisting of stabilised columns crossing one another 1 m beneath the trench floor. An additional stabilisation column wall is added in the middle of the trench. The depth of the column stabilisation varies along with the depth of the pipeline trench.

The construction of streets, water supply systems and the district heating network involves excavation work, earthwork materials such as aggregates and geotextiles, pipes and wells, material transportation, and installation. The removed surface layer is assumed to be used as the substrate in the area. Material transportation is calculated assuming full loads and an empty return. The calculation excludes machinery transportation, workforce-related emissions, and transportation and treatment of excavated soil. Excavated soil is assumed to be used to backfill pipeline trenches and in landscaping. Installation involves laying aggregates and asphalt with an excavator and compacting with a vibratory roller or a plate vibrator. Concrete pipes and wells are installed using an excavator. For details, see File 2 in the supplemental data online.

2.2.4 Case study LCA method and data

LCA calculation method and database

The case study LCA of the buildings applies the Finnish Ministry of the Environment's (MoE) approach (hereinafter the MoE method) (Kuittinen 2019). The method aligns with the European Level(s) framework and standards such as the EN 15643 series (CEN 2012a, 2021), EN 15978

(CEN 2011) and EN 15804 (CEN 2012b). The MoE method only measures the GHG impact (CO_2 equivalents). Each building was assessed using One Click LCA software with a 50-year reference period. The emissions database compatible with the MoE method is the national CO2data.fi, maintained by the Finnish Environment Institute SYKE (SYKE. Suomen Ympäristökeskus 2022). It contains GHG emission factors for various construction products (modules A1–A3). The factors are so-called 'conservative' values, which include a 1.2 multiplier on average GHG emission factors of typical products, intended for use in the initial design stage when specific products are not yet defined, in line with upcoming legislation. For specific LCA modules and building service systems (including those in the building and on the plot), m^2-based tabulated values are used. For module B6, the method includes future decarbonisation scenarios for electricity and district heating. Figure 5 gives the data sources and tabulated values used for buildings.

The LCA for plots and infrastructure construction (module A only) was calculated manually by multiplying material quantities with respective GHG emission factors. For infrastructure materials, the CO2data.fi database provides 'typical' values for GHG emission factors. The individual results of buildings and infrastructure (where relevant) were then incorporated into scenarios.

Emissions, $kgCO_2e/m^2$	RE1	RE2	N1	N2	N3	N4
A. PRODUCT STAGE AND CONSTRUCTION PROCESS (EMISSIONS PRIOR TO USE)						
Product stage						
A1 Raw material supply, **A2** Transport, **A3** Manufacturing	[not included]	[not included]	Project specific	Project specific	Project specific	Project specific
Construction process						
A4 Transport	[not included]	[not included]	10.2	10.2	10.2	10.2
A5 Construction work						
A5 Buildings	[not included]	[not included]	46.0*	46.0*	46.0*	27.3
A5 Materials	[not included]	[not included]	Project specific	Project specific	Project specific	Project specific
A5 Earthworks	[not included]	[not included]	Project specific	Project specific	Project specific	Project specific
B. USE STAGE (EMISSIONS DURING USE)						
B1 Use of products						*[not included]*
B2 Maintenance						*[not included]*
B3 Repair	2.16	2.16	2.16	2.16	2.16	2.16
B4 Replacement	Project specific	Project specific	Project specific	Project specific	Project specific	Project specific
B5 Refurbishment						
$A1_{B5}$ Raw mat. supply, $A2_{B5}$ Transport, $A3_{B5}$ Manufacturing	Project specific	Project specific	[not included]	[not included]	[not included]	[not included]
$A4_{B5}$ Transport	10.2	10.2	[not included]	[not included]	[not included]	[not included]
$A5_{B5}$ Construction work, buildings	46.0*	46.0*	[not included]	[not included]	[not included]	[not included]
$A5_{B5}$ Construction work, materials	Project specific	Project specific	[not included]	[not included]	[not included]	[not included]
$A5_{B5}$ Construction work, earthworks	Project specific	Project specific	[not included]	[not included]	[not included]	[not included]
$C1_{B5}$–$C4_{B5}$	Assumed to be covered by $A5_{B5}$	Assumed to be covered by $A5_{B5}$	[not included]	[not included]	[not included]	[not included]
B6 Operational energy use	Energy simulation	Energy simulation	Average energy consumption	Average energy consumption	Average energy consumption	Not heated, m^2 based electricity consumption**
B7 Operational water use						*[not included]*
C. END-OF-LIFE (EMISSIONS AFTER USE)						
C1 Demolition	7.0*	7.0*	7.0*	7.0*	7.0*	7.0*
C2 Transport	10.2	10.2	10.2	10.2	10.2	10.2
C3 Waste processing, **C4** Disposal	15.6	15.6	15.6	15.6	15.6	15.6
CARBON HANDPRINT						
D Benefits and loads beyond system boundary not included						

Figure 5: Life-cycle assessment (LCA) modules for the buildings, data sources and tabulated values used.

Sources: Ministry of the Environment (MoE) method (Kuittinen 2019): *CO2data.fi (SYKE. Suomen Ympäristökeskus 2022); and **Decree 1010/2017 (MoE 2017).

Product stage (A1–A3)

Two ways were used to quantify materials in buildings: one for the refurbished and extended buildings (RE1 and RE2, including the added civil defence shelter N4) and the other for the new buildings (N1–N3). In RE1, RE2 and N4, the buildings were three-dimensionally (3D) modelled in ArchiCAD software. New building material quantities were derived from the BIMs. For N2, the material quantities were manually calculated from the original drawings and documented using a spreadsheet program. The material quantities were scaled to match the volumes of N1 and N3, as already explained. Material quantities were multiplied by conservative GHG emission factors from CO2data.fi. If a material lacked a factor in the database, an environmental product declaration (EPD) for a commonly used product was selected, although such materials, such as waterproofing, represent a small proportion. For ready-mixed concrete, emissions were calculated using a typical coefficient (0.10 kg CO_2e/kg) rather than a conservative value (0.13 kg CO_2e/kg) to prevent overestimation.

Quantities of plot construction materials (*e.g.* aggregates, geotextiles, asphalt, concrete piles) and infrastructure materials for S3.2 and S3.3 (binder, aggregates, pipes) were manually calculated and multiplied with typical GHG emission factors from infrastructure CO2data.fi. Only the district heating network made an exception. Its emissions were calculated using a running metre-specific GHG emission factor drawn from Kivirinne *et al.* (2024). The emission factor includes phases A1–A5 of the district heating network construction, covering the pipes, trenches, necessary excavation work, transportation and materials. For more detailed information about the materials, see Files 1 and 2 in the supplemental data online.

Construction process (A4–A5)

Emissions from the transportation of construction materials (A4) and construction works of buildings (A5) were determined using tabulated values from the MoE method and CO2data.fi (Figure 5). Emissions from construction site waste (A5 materials and $A5_{B5}$ materials) were calculated for each material based on the waste percentages from the CO2data.fi. Plot earthworks and neighbourhood infrastructure construction process emissions were calculated manually. For module A4, CO_2 coefficients from CO2data.fi were used, with the exception of tank trucks transporting stabilisation binder, for which data from Kivi (2021) were used. Transportation distances were chosen based on product-specific EPDs and the nearest locations of aggregate distributors and material suppliers.

For module A5, GHG emission coefficients for different machines were primarily sourced from CO2data.fi for infrastructure, except for a vibratory roller and stabilisation machinery, whose GHG emission factors were obtained from Kivi (2021). Workflow times were calculated using guidelines for construction works (Rakennustieto n.d.). An exception is the district heating network, where phases A4 and A5 are included in the running metre-specific GHG emission factor, as explained above.

Use stage (B)

Emissions from building repairs (module B3) were determined using tabulated values from the MoE method. Replacement intervals for building components (module B4) were sourced from CO2data.fi and building information file 18-10922 (Rakennustieto 2018). Material emissions were calculated similarly to modules A1–A3. While the MoE method does not include module B5, in refurbished and extended buildings RE1 and RE2, phase B5 was treated like phase A in new construction. Module C_{B5}, *i.e.* demolition of construction existing materials (including the building service systems on the whole plot), in phase B5 was assumed to be covered by module $A5_{B5}$, using tabulated values for new construction (Figure 5).

Buildings' operational emissions (B6) were calculated based on their energy demand from district heating and electricity (without cooling, as it is not required for housing). The calculated consumption of purchased energy of a building is based on standardised use, and consists of energy consumed for heating, ventilation, cooling and domestic hot water as well as for technical equipment, consumer devices and lighting. Thus, it includes the subphases B6.1–B6.3, as defined in the IEA's *EBC Annex 72* (2019). In Finland, energy efficiency requirements exist in regulation for both new (MoE 2017) and refurbished (MoE 2013) buildings. Different methods were used to estimate the energy consumption of new and refurbished buildings. The latter, RE1 and RE2, were simulated with IDA Indoor Climate and Energy (IDA ICE) 4.8 software (EQUA Simulation AB 2022, following standardised usage in Decree 1010/2017 (MoE 2017). They meet the requirements by either halving the *U*-value of the repaired building parts or matching the reference values in the regulation.

Since N1–N3 were not 3D modelled, their energy consumption was based on data from the national energy certification register (ARA 2022). Average electricity and district heating consumption was derived from similarly sized (net heated area ± 10%) blocks of flats completed in Vantaa in the period 2018–22. The register was also used as input data for simulating the energy performance of RE1 and RE2. Averages for air tightness, ventilation heat recovery efficiency, specific fan power, and *U*-values of windows and doors from the register were applied as input values. The civil defence shelter N4, lacking heating or mechanical ventilation, considers only a standardised, square metre-based value for electricity consumption from Decree 1010/2017 (MoE 2017).

The energy consumption of each building was multiplied by GHG emission factors from CO2data.fi, using the decarbonisation scenarios of the MoE method, where the factors decrease over time. Consequently, the GHG impact depends not only on the energy consumption but also on its timing. For detailed input data and the results of energy calculations, see File 1 in the supplemental data online.

No module B emissions were considered for plots or infrastructure due to lack of data.

End of life (C)

End-of-life emissions for buildings were determined using tabulated values from CO2data.fi and the MoE method. No end-of-life emissions were considered for plots or infrastructure.

Allocation of emissions from infrastructure (S3.2 and S3.3)

To the authors' knowledge, there is no established way to allocate emissions from infrastructure construction. If the emissions are simply divided by built floor area, a more efficiently built plot will receive an unreasonably large share. An alternative way is to distribute the emissions inversely in terms of plot efficiency. This way, per square metre emissions become lower on more efficiently constructed plots, such as those for block of flats, than on, for example, single-family house plots. Both approaches are, however, tested in the scenarios: S3.2 divides emissions per built floor area but S3.3 divides them inversely as per plot efficiency.

3. RESULTS AND DISCUSSION

3.1 MODERATE DENSIFICATION

Figure 6 gives the results of the alternatives for moderate densification. Both the retentive scenario (S1) and the replacement scenario (S2) start off with a significant spike from the upfront emissions (module A). The spike of S1 (241 kg CO_2e/m^2) is, however, 35% smaller than that of S2 (372 kg CO_2e/m^2). Despite the differences in energy consumption (9% smaller in S2), S1 has smaller emissions throughout. After 50 years, the accumulated emissions of S1 are 12% smaller than those of S2.

In both scenarios, the vast majority of emissions (99.6% in S1 and 97.9% in S2) are generated by buildings, with only 0.4–2.1% attributed to plots (piles and pavements). During the use phase (B6), emissions in S1 account for 52% and in S2 for 41% of the total. Approximately two-thirds of these emissions originate from district heating (heating, ventilation and domestic hot water), while one-third is from electricity consumption (ventilation, equipment and lighting).

The second most significant source of emissions is upfront embodied emissions (A1–A5), constituting 33% in S1 and 45% in S2 of the total emissions. These emissions are primarily due to materials production. In S1, emissions mainly stem from building systems, followed by windows and doors, and steel structures. In S2, reinforced concrete accounts for over 50%, followed by building systems, and windows and doors. Building construction works (A5) contribute approximately 6% in both scenarios, while demolition of old buildings accounts for 3% in S2 and end-of-life emissions (C) contribute about 4% in both scenarios.

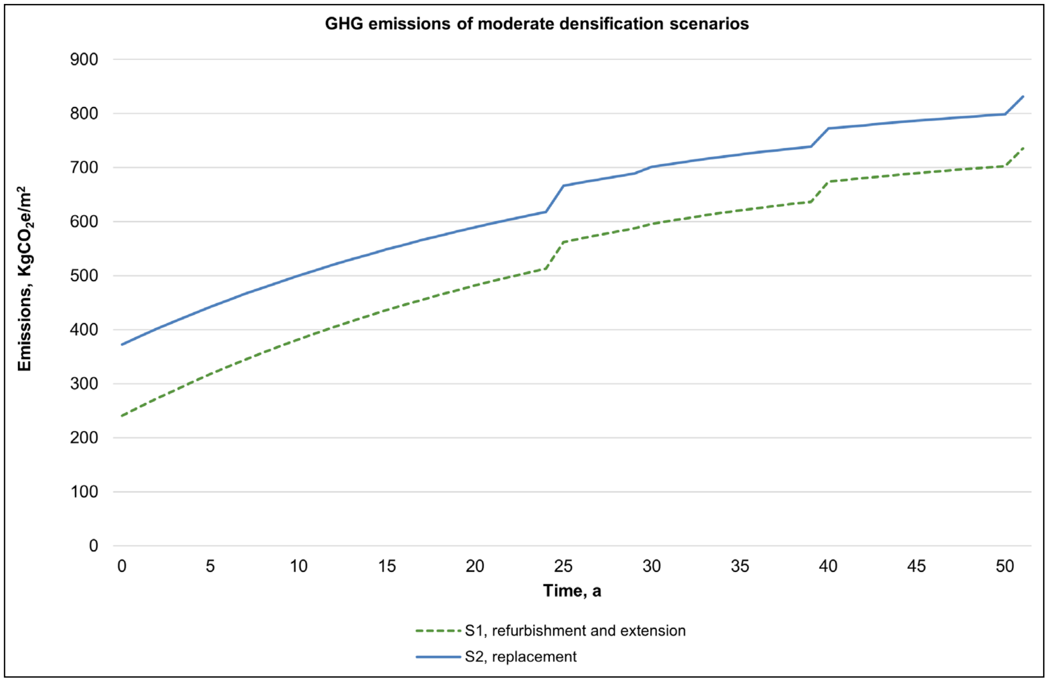

Figure 6: Greenhouse gas (GHG) accumulation of moderate densification scenarios S1 and S2.

Note: Building parts renewals (B4) cause smaller spikes at years 25, 30 and 40 (for details, see File 1 in the supplemental data online). Emissions from possible end of life (C) are also demonstrated at year 50, although demolition is not to be considered inevitable.

3.2 MAJOR DENSIFICATION

Figure 7 gives the results for the alternatives for major densification (refurbishment, extension and infill scenario S3 versus replacement scenario S4). Again, all scenarios have notable spikes from upfront emissions at the beginning, ranging from 277 kg CO_2e/m^2 for S3.1 to 350 kg CO_2e/m^2 for S4. The difference is not as significant as in the moderate densification. At the beginning, the emissions from S3.1 are 21% smaller than those from S4, while those from S3.2 and S3.3 are 11% and 17% smaller, respectively. By year 50, this difference has diminished to 5%, 0.2% and 3%, respectively. The retentive scenario S3 nevertheless continue to have lower emissions over the 50 years, regardless of the infrastructure emissions and how they are allocated.

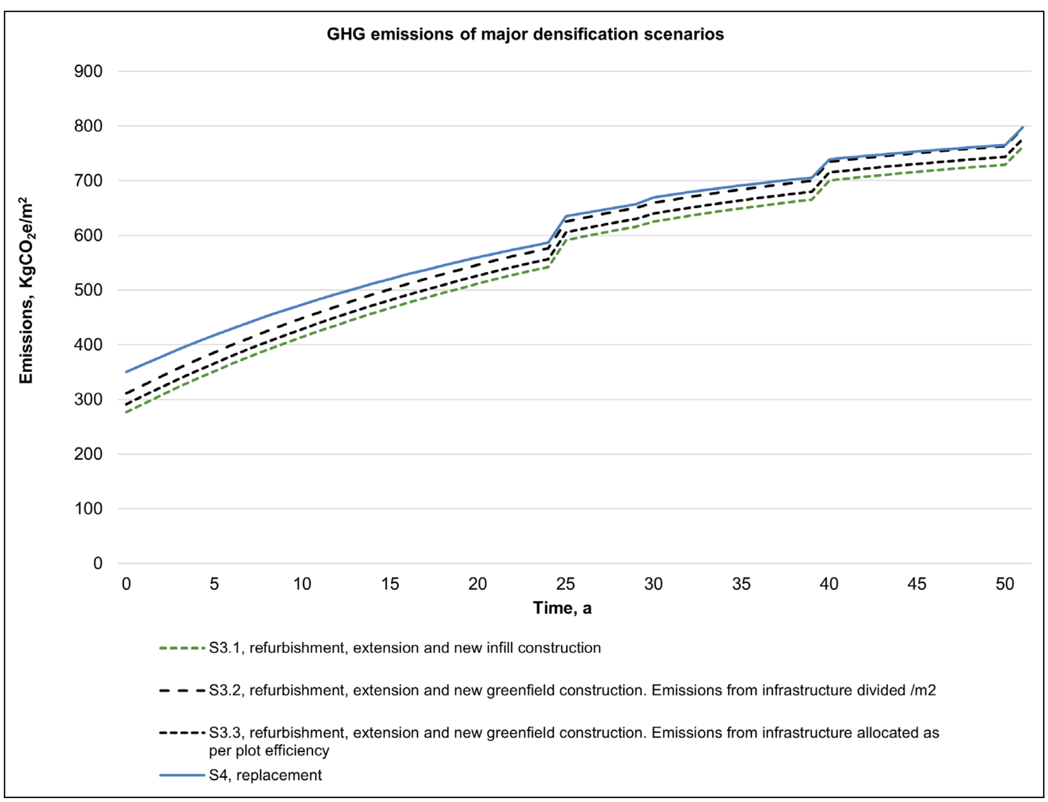

Figure 7: Greenhouse gas (GHG) accumulation of major densification scenarios S3.1–S3.3 and S4.

Note: See Figure 6.

In both S3 and S4, the vast majority of emissions are generated by buildings, with only a small portion attributed to plots. Emissions related to energy consumption in scenario S3 account for 49% of the total, while in scenario S4 they account for 42%.

Upfront embodied emissions (A1–A5) constitute 36% of the total emissions in scenario S3 and 44% in scenario S4. These GHG emissions primarily result from materials production, which aligns with the findings in comparison between S1 and S2.

Building construction works (A5) contribute approximately 6% in both scenarios, while demolition of old buildings accounts for 2% in S4 and end-of-life emissions (C) contribute about 4% in both scenarios.

Infrastructure contributes 6–12% of the emissions of plot 2 (including building N2), which corresponds to 2–4% of the total emissions of scenarios S3.2 and S3.3, depending on the allocation method used. For a detailed table of results, see File 1 in the supplemental data online.

3.3 UNCERTAINTIES AND LIMITATIONS

As any research, the period paper has uncertainties and limitations. Since the same method has been used to calculate the compared scenarios, the inherent uncertainties are fairly similar. They pertain to the assumptions made and data used. For instance, the choice was made that infrastructure emissions were calculated using typical factors, but building emissions were calculated using 'conservative' GHG emission factors, which multiply the typical factors by 1.2. An exception was made for concrete, for which a typical factor was used. However, should the GHG emissions of concrete have been calculated using conservative values, the differences between scenarios would only increase. The same would happen if all materials were calculated with typical values.

Some data gaps affect the scenarios unequally. However, the scenarios have been put together from various components, so any single component has a minimal impact on the overall outcome. Though the differences between scenarios may seem minor at year 50, especially for major densification, substantial changes are required to alter the conclusions significantly. Critical differences may arise from variations in energy efficiency, material quantities or associated GHG emission factors, so country-specific building practices, energy mixes and choices made regarding, for example, energy efficiency can affect the results. In many cases though, existing buildings can be upgraded to meet energy efficiency standards of new buildings as per national regulation, in which building services play a crucial role.

The exclusion of electricity networks is one example of a data gap. However, the GHG emissions from infrastructure construction would need to more than double for the upfront emissions of S3.2 to exceed those of S4 and become fivefold for S3.3 to surpass S4. Moreover, if the capacity of the current infrastructure networks were exceeded due to densification, which was not considered, the same upgrade measures would be necessary whether the densification was achieved through new construction or by extending existing housing.

4. CONCLUSIONS

This paper took the consequential replacement framework (CRF) for buildings introduced by Huuhka *et al.* (2023) and extended the framework from buildings on a singular plot towards the urban scale. This was achieved by investigating more complex urban redevelopment scenarios which necessitate the incorporation of infrastructure. Nevertheless, the extended framework was built in such a way that it enables the user to construct different kinds of scenarios, entailing, for example, refurbishment, extension, infill, replacement and greenfield construction, relevant to the context in question. Therefore, this paper is a building block for including consequential replacement scenarios in fully fledged urban life-cycle assessment (LCA)—a field which is still emerging (*cf.* Goldstein & Rasmussen 2018; Seyedabadi & Eicker 2023). The CRF addresses two shortcomings in urban LCA identified by Goldstein & Rasmussen (2018). First, by examining building replacement, the CRF highlights often overlooked internal dynamics of urban metabolisms, as urban LCAs typically treat the metabolism as a 'black box' using input–output (IO) methodologies.

Second, unlike most urban LCAs, which are cross-sectional, *i.e.* represent a snapshot in time, the CRF offers a longitudinal, dynamic perspective to the accumulation of emissions.

The use of the built environment CRF was demonstrated with the help of a case study in a residential neighbourhood in Finland. Even though most of the published literature only operates at the building level, the results of the infrastructure-extended case study are in line with the previous research (Table 1). Given that existing buildings' operational energy performances are improved close to that of new build, the order of the retention and replacement scenarios is determined by the initial spike from upfront emissions. Without a notable difference in the buildings' energy performances, this order will not change, not even over the long term. Even considering the embodied emissions of infrastructure in the retention scenario that calls for additional new build on a greenfield site (S3.2 and S3.3), the initial spike from upfront emissions is still higher in the replacement scenarios (S2 and S4). In them, the upfront emissions exceed the emissions from 50 years of operation (B6). In the refurbishment scenarios (S1 and S3.1–S3.3) the upfront emissions correspond to only 63–84% of the operational emissions.

As in the current paper, the two previous consequential replacement studies that extend beyond the building level (Heinonen *et al.* 2011; Säynäjoki *et al.* 2012) also conclude that developing existing buildings is lower in greenhouse gases (GHG) emissions. Using IO-based methodology, which is generally considered more 'complete' than a process-based one (*cf*. Goldstein & Rasmussen 2018), Heinonen *et al.* (2011) associated 6% and Säynäjoki *et al.* (2012) 9% of a new residential area's emissions to infrastructure construction. In the present paper's process-based case study, embodied infrastructure emissions comprised 6% or 12% of the new greenfield plot's emissions. Thus, despite the methodological differences, the results are in line across the three studies. However, all three studies are located in Finland. In other contexts, differing results may arise pertaining to climatic conditions or building traditions.

Whether the infrastructure emissions were 6% or 12% in this paper's case study depended on the way they were allocated: directly per floor area or inversely per plot efficiency. The inverse method allocates a lower share and is, in the authors' view, more grounded than the direct allocation, which can be seen to penalise more efficiently built plots. Notwithstanding, even the direct allocation does not change the current case study's conclusion. This is because even if the direct allocation makes the retention- and replacement-based alternatives seem more equal towards the end of the 50-year period, the retention-based scenario is clearly lower carbon right after the decision-making. By the early 2030s, this is when GHG emissions must be cut most urgently to mitigate climate change, as argued by Huuhka *et al.* (2023) when referring to the communications of the Intergovernmental Panel on Climate Change (IPCC).

The case study aimed to demonstrate the use of the built-environment CRF. While it serves as a foundational element for comprehensive urban LCA, it is not yet fully developed, even with infrastructure extensions. This must be considered when interpreting the results, as the impact of greenfield construction (part of S3) extends beyond the case study's scope. Specifically, it leads to additional dynamic emissions, such as GHG emissions from infrastructure repairs and traffic that could not be considered in the case study due to lack of data. Second, building on a greenfield site may involve deforestation, which reduces carbon sinks. Third, greenfield construction also calls for new urban service networks, such as public and commercial buildings, which were not included at this time due to complexity.

To advance urban LCA, research should next focus on broader aspects and their impacts. A comprehensive understanding is essential to make informed policy decisions and reduce emissions in urban areas, regardless of who are the decision-makers, and which policy instruments are in use, as these vary by context. Based on the current and previous case studies, policies should prioritise improving the energy efficiency of existing buildings and extending their lifespan. Furthermore, extending buildings can be a GHG-efficient alternative to replacement for meeting increasing demands for new homes and other facilities in growing cities. Comprehensive urban LCA will help validate or challenge these propositions in diverse climatic contexts. Considering other impact categories in addition to GHG emissions, as well as the effects of future climates (*cf*. Huuhka *et al.* 2024), could also yield more nuanced results. They represent further topics for future research, so the complexity of urban LCA remains a challenge for the LCA community.

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COMPETING INTERESTS

Satu Huuhka is an editorial board member of the journal, but had no role in the peer review or decision processes with this manuscript. No other competing interests are reported by the authors.

DATA ACCESSIBILITY

The data that support the findings of this study are supplied in the tables/figures and Files 1–2 in the supplemental data online. Additional data, such as greenhouse gas emission factors, are available from open-access sources such as the CO2data.fi database (SYKE. Suomen Ympäristökeskus 2022) and the Ministry of the Environment (MoE) method (Kuittinen 2019). To assist readers, information on carbon intensity is also included in File 1 in the supplemental data online.

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SUPPLEMENTAL DATA

Supplemental data files can be accessed at: https://doi.org/10.5334/bc.472.s1

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