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RESEARCH

A layered dynamic material flow framework for modeling building renovations

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Abstract
Dynamic material flow analysis (dMFA) is widely used to study the material demands of residential building stocks. In most of the studies conducted to date, buildings are modeled as homogeneous units instead of a system of components. A limitation of this assumption is that the material flow dynamics from renovations cannot be fully captured. In this study, we develop a cohort-based, layered dMFA framework that explicitly links renovation lifetimes to structural lifetimes, while allowing for different building layers to be renovated independently. This framework tracks the temporal evolution of building cohorts and applies a lifetime convolution approach to ensure that renovation probabilities are conditional on building survival. Cohort-specific material intensities are further differentiated across structural, skin, and space layers. We apply the framework to residential buildings in Sweden using a unique set of building inventory and disaggregated material intensity data. Compared with conventional monolithic renovation models, the layered lifetime approach reduces the estimated renovated floor area by approximately 10%, with larger differences seen for older cohorts that are approaching demolition. These corrections translate into substantial changes in renovation-related material flows. The results demonstrate that neglecting lifetime interdependencies between building components and structures leads to inflated estimates of the demand for renovation. By conceptualizing buildings as systems that have components with interrelated lifetimes, this study advances dMFA methods for renovation modeling.

Keywords Dynamic material flow analysis · Material stocks · Residential buildings · Renovations

1 Introduction

The global building and construction sector is a major driver of material usage, energy consumption, and greenhouse gas emissions (GHG), accounting for more than one-third of the final energy demand and a comparable share of energy-related CO_2 emissions worldwide (United Nations Environment Program, 2025). In regions with mature building stocks, demographic stabilization and slowing rates of new construction, GHG mitigation strategies are shifting away from continuous expansion toward the transformation and lifetime extension of existing buildings. Thus, renovation plays an increasingly crucial role in efforts towards improving climate mitigation and increasing resource efficiency, as it determines the length of time that existing materials remain in use, as well as the extent to which new materials are introduced into the system.

Dynamic material flow analysis (dMFA) is widely used to quantify the material stocks, inflows, and outflows associated with building construction and demolition (Augiseau & Barles, 2017). By tracking the accumulation, usage, and retirement of materials over time, dMFA enables consistent estimations of construction demands, demolition wastes, and in-use stocks across building cohorts (B. Müller, 2006). In most building stock dMFA applications, demolition is modeled through lifetime distributions applied to building structures. Renovation activities, however, are typically

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represented in a simplified manner, either as fixed annual renovation rates (Zhang et al., 2021) or as independent renovation cycles that are statistically decoupled from demolition probabilities (Ohms et al., 2024).

A common modeling assumption behind the simplification of renovation modeling is that buildings are represented as single, homogeneous units in dMFA studies. As reviewed by Mohammadiziazi and Bilec (2022), at the time of their writing, 80% of their reviewed studies did not distinguish between materials accumulated in structural and non-structural components. The exception being Stephan and Athanassiadis (2017, 2018) quantified material stock and flow while differentiating between structural and non-structural materials without explicitly modeling renovation activities. If buildings are modeled as single units, the temporal dynamics between different components driven by renovation are not fully captured.

The temporal dynamics that is not captured is the differences in lifetimes for different building components (Bertin et al., 2020). Architectural theory and empirical evidence conceptualize buildings as assemblies of components with distinct functions, material compositions, and longevities (Gobbo et al., 2024). Structural elements typically determine the end of a building's service life (EoL), whereas non-structural elements (such as façades, roofs, and interior partitions) are replaced repeatedly through renovations, without triggering demolition. The observed renovation frequencies vary significantly across these components, reflecting technological obsolescence, functional changes, and maintenance practices (Andersen & Negendahl, 2023). Capturing this heterogeneity is essential for the realistic modeling of renovation dynamics.

Despite this, most existing dMFA approaches experience limitations in simultaneously representing component-specific renovation dynamics and their dependencies on structural lifetime. Although the frameworks developed for other component-based products provide useful conceptual insights, they are not directly extrapolatable to buildings (Aguilar Lopez et al., 2022), where the replacement of non-structural components does not induce system-level obsolescence and demolition decisions are often driven by economic or planning considerations rather than material failure (Daigo et al., 2017). Building-specific approaches that introduce renovation cycles or renovation rates improve the temporal resolution but generally lack the ability to link renovation probability explicitly to demolition risk, while maintaining cohort-level detail for multiple building layers (Džubur & Laner, 2018; Roca-Puigròs et al., 2020). There is therefore a need for dMFA models that can capture the dynamics of obsolescence between different building components.

The aim of this paper is to introduce a new dMFA modeling approach that divides buildings into their shearing layers and to compare the differences in results between the layer-based and the traditional monolithic approaches. The hypothesis of this study is that by modeling renovation dynamics as dependent on structural lifetime, the new approach yields a lower amount of renovated floor area compared to the traditional approach. We hypothesize that buildings are unlikely to be renovated close to demolition, and the traditional approach does not capture this detail.

The rest of the paper is structured as follows: we introduce the shearing layer concept to building stocks, to enable the modeling of building as a product with multiple components (herein referred to as *layers*) (Sect. 2). In addition, we describe the main contribution of this work, which is the layer renovation model (LRM) (Sect. 3). The value of the framework is demonstrated by a case study in which we estimate the material flow from residential buildings renovations in Sweden (Sect. 4). In Sect. 5, we show the results of the case study, while Sect. 6 comprises discussions of the assumptions, limitations, and future work. The conclusions drawn from this work are presented in Sect. 7.

2 Conceptualizing buildings as layered systems

A common assumption made in the modeling of building material stock is that buildings behave as a single product and thus have a single lifetime. This assumption is in strong disagreement with the architectural concept of a building layer, which has become an increasingly central theme in the circular construction literature, and which states that "There isn't any such thing as a building. A building properly conceived is several layers of longevity of built components" (Duffy, quoted in Brand, 1995). Indeed, the vast majority of buildings are not monolithic; rather, they are composed of multiple parts, each with their own lifetime (Brand, 1995). Brand (1995) has proposed the following six layers for a building: site, structure, skin, space, services, and stuff (See Fig. 1). When it comes to material stock (MS) modeling of the built environment, three of the six layers are particularly relevant: the structure; the skin (i.e., the building envelope); and the space. The latter refers to the building elements that subdivide the space within the building and that are not part of the structure, such as partition walls, ceilings, and flooring. Each layer has a specific lifetime, making their differentiation particularly critical when investigating the renovation dynamics of a building stock. Indeed, buildings typically undergo multiple renovations over their lifetime, with each renovation focusing on a specific layer (Brand, 1995). For example, renovation of the façade of a building (skin layer) does not always happen at the same time as the changing of the interior layout of a building (space layer). Therefore, to capture accurately the complex dynamics of

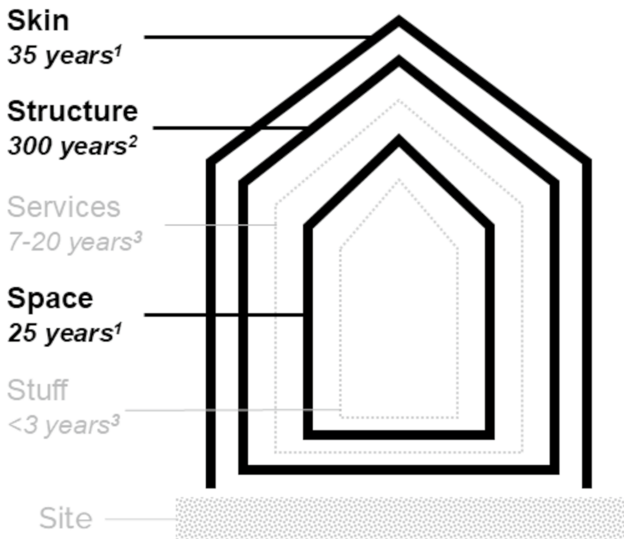


Fig. 1 Demonstration of the layers; adapted from (Lanau et al., 2026). 1. The skin and space lifetimes are derived from (Sartori et al., 2016). 2. The structure lifetime is assumed based on the empirical demolition rate in Sweden (Statistics Sweden, 2026). 3. The service and stuff lifetimes are taken from (Stankovic et al., 2015)

building renovation activities, it is essential to model the material stock and flow at a higher level of granularity, so that the different longevities of the layers are represented. Thus, dividing a building into its layers can make building dMFA models more representative of real-world conditions.

The concept of layers allows buildings to be treated as long-lived products composed of multiple layers. The product is the building, with the structure layer being the critical determinant of product obsolescence. In addition, there are two non-critical layers (skin and space), which can be renovated multiple times while the product remains in use. In addition, material intensities tend to differ by building construction age, which means that the materials required for the renovation of buildings in each cohort will differ. We have developed a model framework based on these unique characteristics of buildings.

3 Methodology

The generic framework developed in this study follows this logic in a step-by-step manner:

(1) We calculate the gross floor area (GFA) dynamics (stocks and flows) from construction and demolition activities, using a first stock-driven dMFA (Sect. 3.1.1);
(2) We then estimate the GFA dynamics (flows) from renovations activities, using two stock-driven dMFAs (Sect. 3.1.2) running in parallel for the skin and space layers;
(3) Subsequently, we convert the flow results into material quantities, using material intensities (MIs) (Sect. 3.1.3);

Using dMFA, we leverage bottom-up building inventory data and a detailed material intensity dataset (disaggregated across the building layers), to capture renovation activities across different building layers. By adapting the lifetime convolution method introduced by Sartori and coworkers (Sartori et al., 2016), we develop a method for linking the renovation of buildings layers to the probability of demolition. To estimate the uncertainties associated with building dimensions and material intensities, we add a parametric stock and flow model. Thereafter, we exemplify the application of the model using residential buildings in Sweden, owing to good availability of relevant data. Lastly, we compare the results with those of previous studies and discuss the model, its results, and the contributions of this research to the wider research field.

3.1 Dynamic buildings stock modeling

Building stock dynamics are modeled using two bottom-up, stock-driven dMFA models. The first stock-driven model estimates the future inflow (i.e., new construction), the outflows (i.e., demolition), and the stock of usable floor area based on different age cohorts. The second stock-driven model uses the projected surviving stock to simulate renovation needs, applying layer-specific lifetimes for the building's skin and space layers in order to estimate the renovation dynamics. The dMFA models are coded in Python using the Open Dynamic Material Systems Model (ODYM) (Pauliuk & Heeren, 2020).

We assume a Weibull distribution for demolition, with a scale of 300 and shape of 3 for all buildings built after Year 1920. We chose the Weibull distribution as it is commonly used in literature, and the choice of lifetime distribution does not significantly impact results (Miatto et al., 2017a). The rationale for choosing these parameters is to calibrate the demolition rate to statistical data. There is no official data for SF building demolition rate, and in 1400 MF buildings were demolished in 2024, which corresponds to a demolition rate of approximately 0.05% of the existing building stock (Statistics Sweden, 2026).

The lifetime distributions for renovation are often modeled as cycles or a fixed lifetime distribution (Sartori et al., 2016; Yang et al., 2022). We assume a normal distribution with mean lifetimes of 35 years for the skin layer and 25 years for the space layer, which are in line with the National Renovation Strategy (Ministry of Infrastructure, 2020).

3.1.1 Structural stock-flow model

The first stock-driven dMFA models the outflow of floor area from the existing stock (i.e., demolition), using Eq. (1). The stock-driven model calculates the outflow using a survival function, which represents the share of the inflow from age-cohort c remaining in the stock at time t. This specific survival function represents the lifetime of the structure layer, and a building is assumed to be demolished if the structure reaches its EoL. There is a lack of consensus in the literature regarding the functional forms of lifetime distributions (Zhong et al., 2021), although the Weibull distribution is most commonly used and has the largest amount of available data (Deetman et al., 2020).

$$O_{i,c}(t) = \sum_{\tau=t_0}^{t} I_i(\tau) \times \left(1 - surv_{structure,c}(t-\tau)\right) \tag{1}$$

where $O_{i,c}(t)$ is the outflow of floor area of building type i from age-cohort c at timestep t (in m^2), $I_i(\tau)$ is the inflow of floor area of building type i in year τ, and $surv_{structure,c}(t-\tau)$ is the share of GFA of building structures from age-cohorts c that are still standing after (t—τ) years.

The next step is to calculate the inflow of building type i at time t using the mass-balance principle, as shown in the following set of equations:

$$\begin{cases} S_{survive_{i,c}}(t) = \sum_{\tau=t_0}^{t} \left(I_{i,c}(\tau) - 0_{i,c}(\tau)\right) \\ I_i(t) = S_i(t) - S_{survive_i}(t) \end{cases} \tag{2}$$

where $S_i(t)$ is the actual stock of building type i at time t, and $S_{survive\,i}(t)$ is the surviving stock of building type i at time t after $outflow_i(t)$ is removed. Equations (1) and (2) are used for the monolithic model, where three stock-driven models are run in parallel. The first stock-driven model uses a scale of 300 and shape of 3 to represent demolition, and the other two stock-driven models assume a fixed lifetime of 35 and 25 to represent renovations of the skin and space layer.

3.1.2 Renovation modeling with layer-specific lifetimes

In the LRM, renovation activities are modeled with an additional stock-driven MFA applied to the surviving stocks from each age-cohort. First, only the surviving stock from each age-cohort is subject to renovation. Therefore, the lifetime convolution method proposed by Sartori et al., (2016) – which ensures that no demolished buildings are renovated – is adapted. The main concept behind the approach is that demolition happens only once, but renovation happens multiple times in cyclical fashion. The implementation of this approach is by shifting the lifetime profile by the mean renovation cycle (e.g., 25 years) to ensure that a building's expected lifetime after renovation is at least as long as the renovation lifetime itself. We adapt and apply this approach to the skin and space layer using specific survival curves, using the following equations:

$$O^R_{i,c,L}(t) = \sum_{\tau=t_0}^{t} I^R_{i,c}(\tau) \times \left(1 - surv_{L,c}(t-\tau)\right) \tag{3}$$

$$S^R_{S,i,c}(t) = \sum_{\tau=t_0}^{t} \left(I^R_{i,c}(\tau) - O_{i,c}(\tau)\right) \tag{4}$$

$$I^R_i(t) = \sum_c S_{S,i,c}(t) - S^R_{S,i,c}(t) \tag{5}$$

where $O^R_{i,c,L}(t)$ is the outflow of renovated floor area of layer L of building type i from age-cohort c at time t (in m^2), $I^R_i(t)$ is the inflow of floor area or renovation of building type i (in m^2), and $Surv_{Lc}(t-\tau)$ is the survival function that represents the share of the inflow from age-cohort c remaining in the stock at time t. These equations are applied to both the skin and space layer in parallel, as we assume that skin renovation for functional maintenance and space renovation for changing internal layout happens independently.

This specific survival function is used to represent the lifetime of the layer (skin or space), and a building requires renovation if the layer (skin or space) reaches its EoL. As a stock-driven model is applied to each age-cohort c, the total amount of floor area in need of renovation at time t is calculated by summing across all the age-cohorts for each time t, as shown in Eq. (5).

3.1.3 Material stocks and material flows

The in-use MS is calculated by multiplying the floor area by its relevant material intensity, as shown in Eq. (6):

$$\begin{cases} MS_{i,m,L}(t) = \sum_c MI_{i,c,m,L} \times S_{i,c}(t) \\ L = \{\text{structure; skin; space}\} \end{cases} \tag{6}$$

where $MS_{i,m,L}(t)$ is the MS in building type i for material type m at time t for layer L, $MI_{i,c,m,L}(t)$ is the material intensity of material type m for layer L in building type i of cohort c. The rationale for this formula is that buildings from different cohorts have different material intensities, and within these buildings, the building layers also have different material intensities.

Lastly, the inflows associated with renovations are calculated using Eq. (7):

$$\begin{cases} m_{I^R_{i,m,L}}(t) = \sum_c MI_{i,c,m,L} \times I^R_{i,L}(t) \\ L = \{\text{skin; space}\} \end{cases} \tag{7}$$

where $m_{I^R_{i,m,L}}(t)$ is the inflow of construction material from renovations of building type i of material type m for layer L at time t (in kg/year), $MI_{i,c,m,L}(t)$ is the material intensity of material type m of layer L of building type i of cohort c (in kg/m^2), and $I^R_{i,L}(t)$ is the inflow of GFA of layer L being renovated at time t (in m^2).

4 Case study

4.1 Scope of study

We use the framework of Lanau et al. (2019) to define the scope of this study. With regards to end-uses, we limit the scope to residential buildings – single-family (SF) and multi-family (MF) dwellings. We exclude non-residential buildings due to a lack of data. The residential building stock is measured using usable floor area (in square meters), materials (in tonnes). The spatial boundary is Sweden, with no further spatial resolution. Lastly, the study is prospective, with a temporal scope spanning Years 2025 to 2050. To better demonstrate the stock dynamics of renovations, we exclude new construction and assume that the stock does not grow.

4.2 Data sources and data quality

We present the key data sources used in this case study, together with reflections on the quality of the data and a presentation of the key assumptions made.

4.2.1 Building inventory data

The real estate registry from the Swedish Land Survey (*Lantmäteriet*) (Lantmäteriet, 2023) contains information on the use, construction year, and GFA of the 2.8 million residential buildings in Sweden. The construction years or cohort of buildings in the initial stock ranges from Year 1880 to Year 2022. The GFA does not include attics or basements. The quality of the building inventory varies across the various attributes. The building use type data is considered reliable, as the inventory is used for tax purposes. Since neither the construction year data nor GFA data are complete, missing values were predicted using the machine learning models developed in a previous study (Liu et al., 2026). Therefore, the inventory data represents a hybrid of real and predicted values.

We retrieved data on building structure from the work carried out by Bian et al., (2026), in which they used building morphological indicators to predict the structures of residential buildings in the city of Gothenburg. Their results showed high prediction accuracy ($>80\%$), and we use them in this study to be able to apply Swedish MIs (which follow a structure-use-age archetype) to the inventory.

Buildings constructed before 1920 are assumed to be preserved for their cultural heritage value and are, therefore, not demolished, even when they reach their EoL.

4.2.2 Material intensity data

Building archetypes are categorized in the same way as in the MI study of Gontia et al., (2018), namely across two uses (SF and MF buildings), four structure types, and 12 age categories (Lanau et al., 2026). The structure types include Wood multi-family (WMF) buildings; Wood-brick multi-family (WBMF) buildings; Brick multi-family (BMF) buildings; and Concrete multi-family (CMF) buildings. The MIs are presented in kilograms per square meters of GFA, across 10 construction materials (see Supplementary Information SI2).

We retrieved, restructured, and recalculated the Swedish residential MIs reported by Gontia and colleagues (Gontia et al., 2018) using the BUD-MI data collection template (Lanau et al., 2026). In BUD-MI, each building item was tagged to its relevant layer, and in the case of the structure, it was tagged based on whether it was the super-structure or sub-structure. This tagging process allowed the generation of four MIs per archetype: a skin-MI, a space-MI, a substructure-MI, and a superstructure-MI (shown in kg/m^2 of GFA). Substructure refers to the part of the structure up to the lowest face of the lowest floor covering, and superstructure refers to the part of the structure from the lowest face of the lowest floor covering up. The sum of these four MIs corresponds to the typical building-level MIs used in the bottom-up approach.

It is worth noting here that the extensive dataset of material densities in BUD-MI was used during the recalculation. For example, pinewood density was used rather than the average density of timber. The rules of thumb available in BUD-MI were also used to calculate, for example, the share of reinforcements in reinforced concrete, or the share of mortar and bricks in masonry. In addition, when relevant and in consultation with experts in Swedish construction, we tweaked a few assumptions to reflect more accurately the descriptions of the construction techniques described in the source material (Björk et al., 1983, 2009), of which the depth of foundation was the most-significant update.

As a result of these recalculations, in this work, the average total MIs were: 557 kg/m^2 GFA for MF; and 1,054 kg/m^2 GFA for SF. For comparison, Gontia et al. (2018) calculated 838 kg/m^2 GFA for MF, and 1,295 kg/m^2 GFA for SF. However, two key sources of uncertainty persist that are relevant to this work. The first concerns the thickness and density of the insulation materials in the roof and walls, neither of which are properly specified in building plans. The second source of uncertainty pertains to concrete foundation footings, for which the depth and thickness are not specified. The depth, which varies according to the geology of the ground underneath the building, can significantly affect the total MI.

5 Results

5.1 Material stock

To demonstrate the model framework, we need to understand both the material stock composition based on layers and the evolution of the stock composition over time, as presented in Fig. 2. The MS for residential buildings in Sweden in 2024 was 354 Mt, which is equivalent to 33 tonnes per capita (t/cap). As shown in Fig. 2(a, b), MF buildings make up most of the residential material stock at 210 Mt (59%), as compared with 144 Mt (41%) for SF buildings. In total, the building structures amount to 81% (286 Mt) of the total amount of Sweden's residential material stock. However, one needs to highlight the impacts of MI-related assumptions on these results.

The MS for SF buildings has increased by 112 Mt, from 65 Mt in Year 1920 to 177 Mt in Year 2024, which represents a 279% increase. In comparison, the MS for MF stock has increased by 81 Mt, from 6 Mt in Year 1920 to 87 Mt in Year 2024, which represents a 927% increase over the same period. The differences in the percentage increases

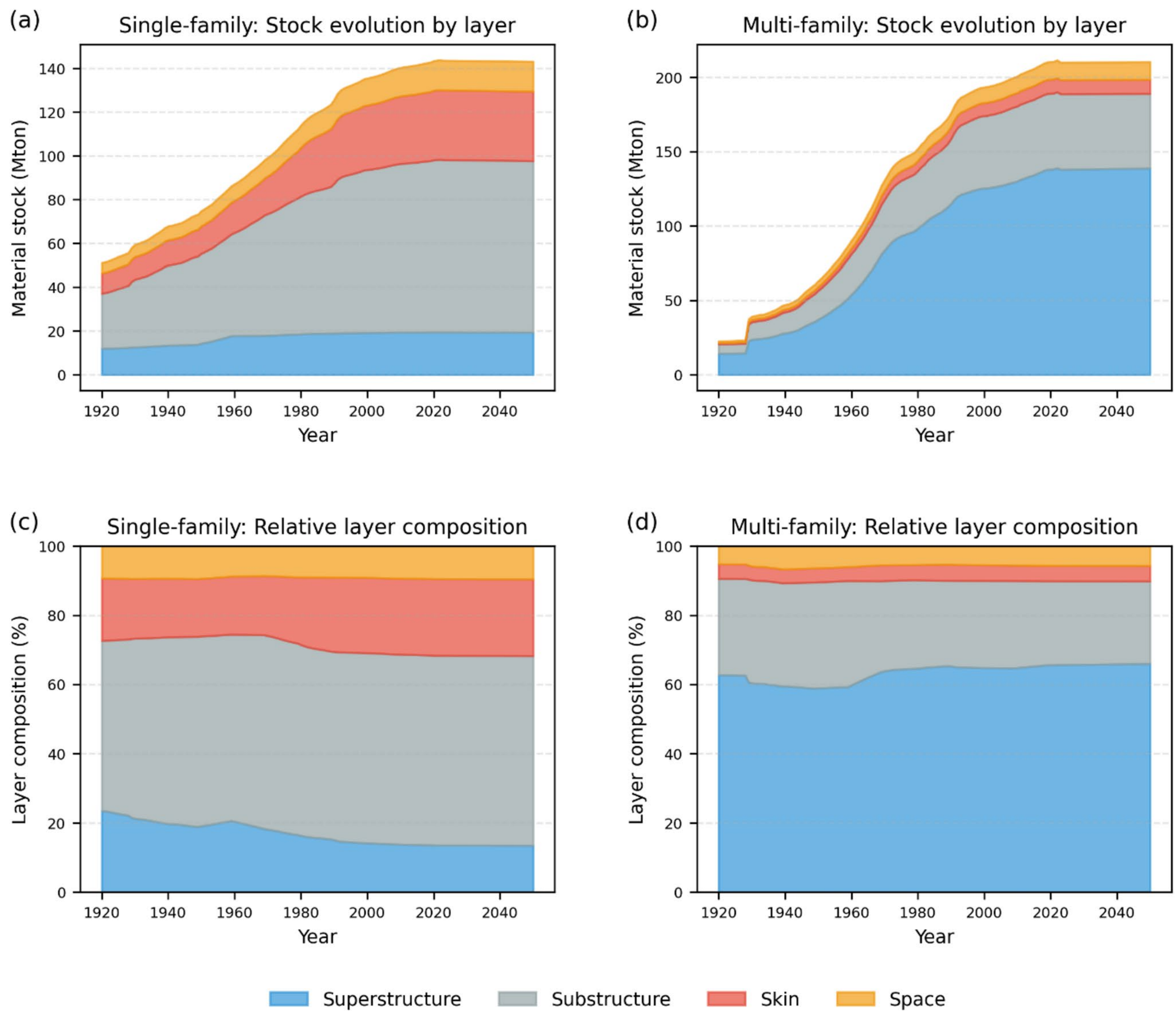


Fig. 2 Evolution of the material stock over time by layer for single-family buildings **a** and multi-family buildings **b**, and evolution of the material stock composition by percentage for each layer for single-family buildings **c** and multi-family buildings **d**. The data for Fig. 2 can be found in Supplementary Information SI1

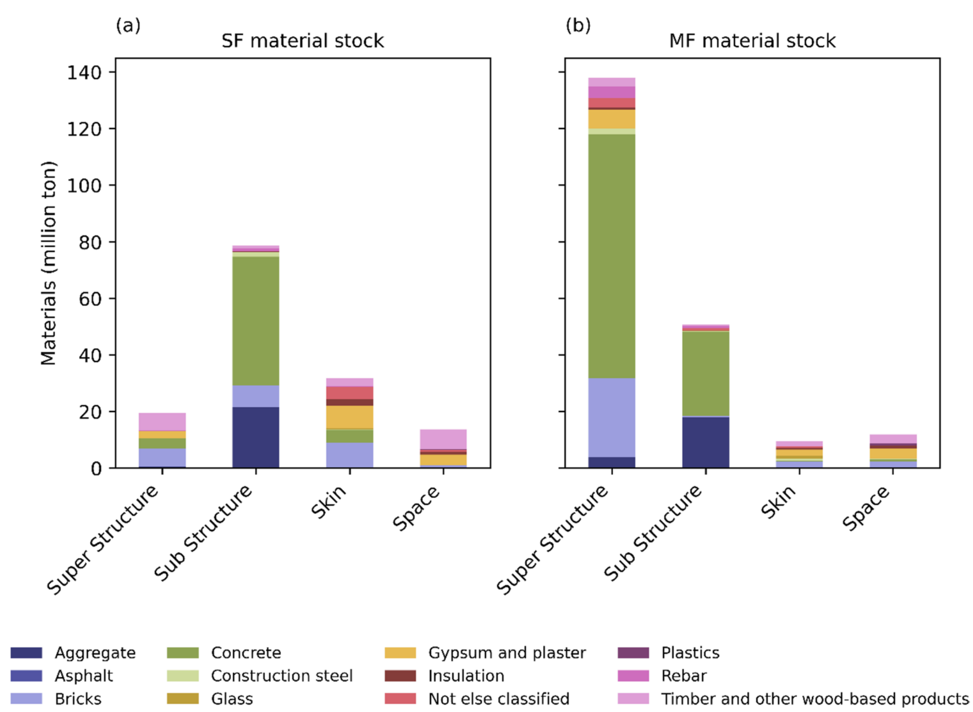
in MS stock indicate that Sweden has been building more MF buildings due to an increasing urbanization rate. The evolutions of layer composition of the MS for SF and MF buildings are shown in Fig. 2(c, d). The share of each layer as a percentage of the total MS for both SF and MF buildings is relatively stable, as compared with the evolution in total MS. For SF buildings, the share of space layer MS as total MS has remained stable, from 9.35% in 1920 to 9.6% in Year 2024, while the superstructure layer's share has declined from 24% in 1920 to 14% in 2024. The share of substructure layer has increased from 49% in 1920 to 54% in 2024, and the share of skin layer has increased from 18 to 22%. The evolution of layer composition for SF buildings can be explained by the increased use of concrete in substructures, and the increased use of gypsum and plaster in the space layer. The layer composition of MF buildings is more stable compared to that in SF buildings, as the shares of superstructure, substructure, skin, and space layer have only changed from 63%, 28%, 4%, and 5% in 1920 to 66%, 24%, 4%, and 6% in 2024, respectively. The stability of the layer composition can be explained by the relatively similar techniques used for the construction of MF buildings in Sweden.

The detailed material composition of the MS in each building layer for the SF and MF buildings in Year 2024 is shown in Fig. 3(a, b). The distribution of material stocks across the layers displays different patterns for the SF and MF buildings. For both, the structure layer stocks contain most of the construction materials: 68% of the SF stocks (98 Mt), and 90% (189 Mt) of the MF stocks. It is noteworthy that the vertical distribution differs depending on the building's use. The *sub*structure is the largest contributor to the SF stocks (79 Mt, 55% of the SF stocks), while the *super*structure dominates the MF stocks (138 Mt, 66% of the MF stocks). Regarding composition, unsurprisingly, the substructures are dominated by concrete and aggregate in both the SF and MF stocks. The superstructures show greater material variety: in the SF, bricks and timber dominate the composition, whereas bricks and concrete predominate in the MF.

Among the non-structural layers, the skin layer is the second-highest weight contributor to the SF stocks, amounting to 31 Mt (22% of the SF stocks), which is heavier than the superstructure (19 Mt, 14% of the SF stocks). There are two reasons why the skin layer contributes more than the superstructure layer to the SF stocks. First, buildings have a larger roof to usable floor area ratio and, thus, have proportionally more material in the roofs. Second, we see a large share of timber in SF superstructures. This results in the skin layer weighing more than the superstructure layer in the Swedish SF stock. In contrast, the skin layer contributes minimally to the total MF stock (9.5 Mt, 4% of the MF stocks).

As regards the space layer, it is a weak contributor to both the SF and MF stocks, amounting to 10% of the SF stocks (14 Mt) and 6% of the MF stocks (12 Mt). Material-wise, the space layer is dominated by timber, gypsum and plaster in the SF, and by gypsum and plaster in the MF (with timber having a smaller share). This reflects the function of the space layer, which includes building elements such as ceilings (timber and plaster), drywalls (timber and plaster), and flooring (timber).

Fig. 3 Material stocks for Swedish residential buildings. The SF material stock **a** and MF material stock **b** are shown to demonstrate the differences between the material stock distributions across layers. The data for Fig. 3 can be found in Supplementary Information SI1



5.2 Renovation material flows

Figure 4(a, b) shows the material flow results for the skin and space layers in the SF buildings and MF buildings in Fig. 4(c, d).

The inflows of material from renovation activities from Year 2024 to Year 2050 show significantly different trends. Overall, the results indicate that SF buildings require substantially more renovation materials than MF buildings in absolute terms. In total, the levels of materials required for the renovation of SF buildings range from 1.4 Mt in 2025 to 1.6 Mt in 2050, while the levels of materials required for the renovation of MF buildings range from 587 kt in 2025 to 589 kt in 2050. However, the materials required for skin and space layer renovations differ between the SF and MF buildings. For SF buildings, the skin layer requires more materials for renovation at 880 kt in 2025 than the 511 kt required by the space layer. On the other hand, for MF buildings, the skin layer requires less material for renovation, at 262 kt in Year 2025 compared to the 325 kt required by the space layer in Year 2025. This difference can be explained by the difference in MI for the skin and space layers. In total, the MI of the skin layer for SF buildings contains 123 kg/m^2 of materials, while the MI of the space layer is only 53 kg/m^2 of materials. In contrast, the MI of the skin layer for MF buildings contains 47 kg/m^2 of materials, while the space layer contains 60 kg/m^2 of materials.

Another notable finding is that the material flows from the renovation of the space layer in SF buildings exhibit less variability compared to the other building layers. Since the same lifetime distribution is used for the space layers of the SF and MF buildings, this variability difference is likely due to the construction year distributions of the SF buildings.

5.3 Layer renovation model

To test the hypothesis of this study, we compare the inflows of floor area for renovations between the monolithic model and the LRM, as shown in Fig. 5. The results are presented separately for SF and MF buildings, to highlight the effect of the age-cohort composition on the framework, given that the magnitude of the differences in results of renovation activities differs based on the age-cohort composition of the model building stock.

The total amounts of renovation (in m^2 of GFA) from Year 2025 to Year 2050 for SF and MF buildings are shown in Fig. 5 (a and b).

For SF buildings, it is clear from Fig. 6a that the results from the layered model follow the renovation cycles, while the results from the monolithic model do not. In Year 2050, the difference in GFA renovated is around 800,000 m^2, which represents a 4.2% difference. This rather small difference is most likely due to the relatively small proportion

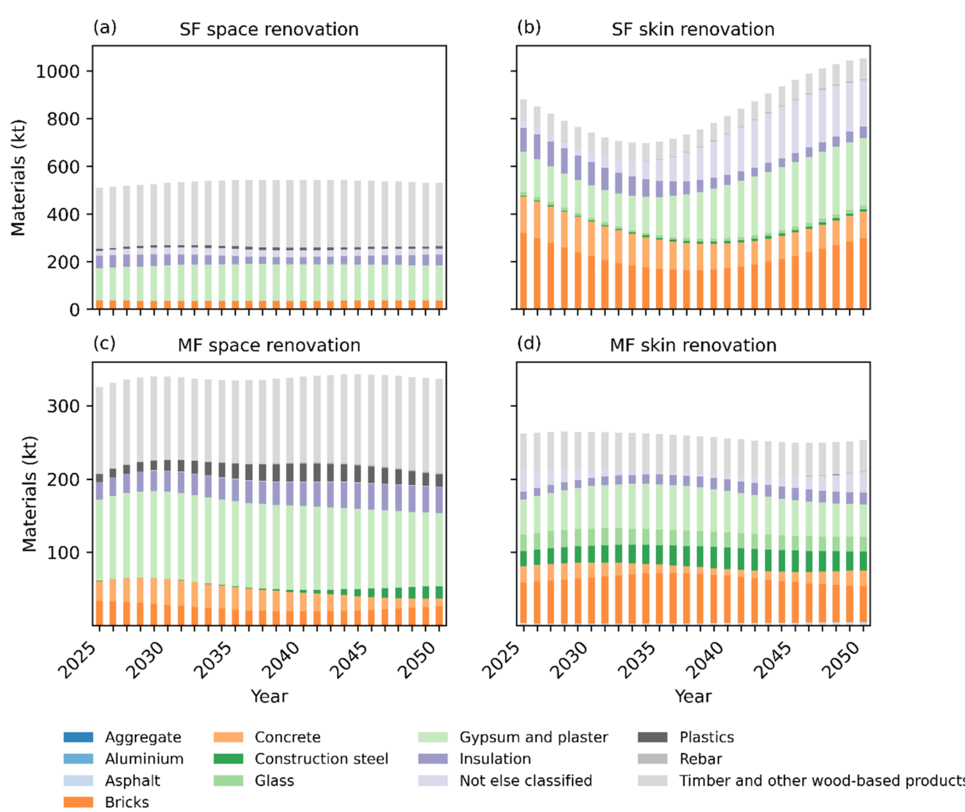


Fig. 4 Inflows of materials from renovation activities for the skin and space layers of SF buildings (**a** and **b**) and MF buildings (**c** and **d**), respectively. Note that the y-axis is shared between each row and is different for the SF and MF buildings. The data for Fig. 4 can be found in Supplementary Information SI1

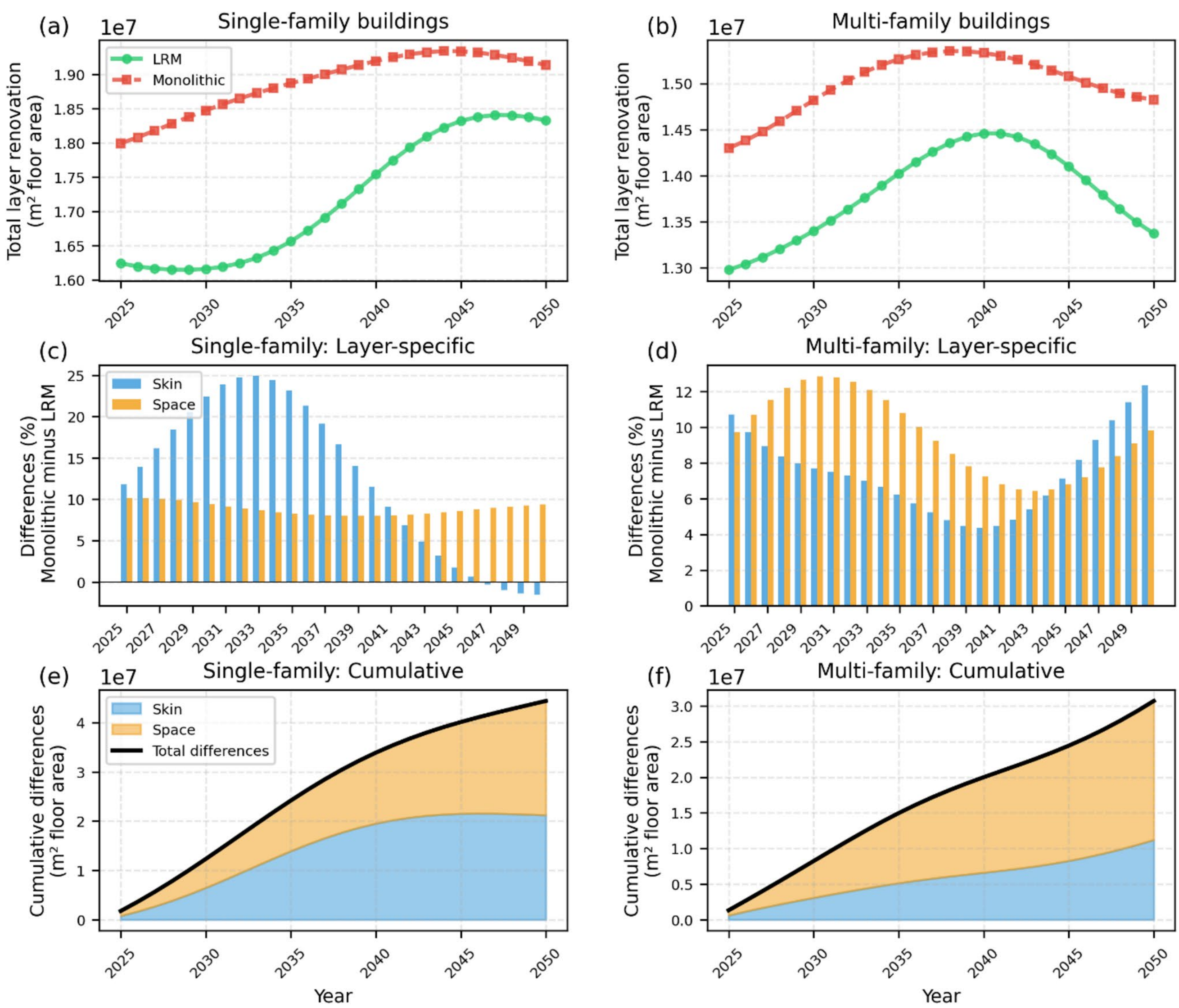


Fig. 5 Comparison of the inflows of floor area from renovation activities between the monolithic and LRM (**a** and **b**). Shown are the percentages differences of renovations from the monolithic model for each layer (**c** and **d**), and the cumulative differences of renovated floor area (**e** and **f**). The data for Fig. 5 can be found in Supplementary Information SI1

of SF buildings that are close to demolition, and thus the layered model is not renovating these buildings.

The trend in the results is more similar between the monolithic model and the layered model for the MF buildings. The difference in GFA renovated in Year 2050 for MF buildings is 1.3 million m^2, which is only an 8% difference. This difference is most likely due to MF buildings on average being built later and thus being further in time from demolition.

The differences in results from the monolithic model for each layer are presented in Fig. 5 (c and d). For SF buildings, on average over the modeled period, the monolithic model shows higher renovated GFA of 12.6% and 8.8% for the skin layer and space layer, respectively. For MF buildings, on average, the monolithic model shows higher renovated GFA of 7.4% and 9.5% for the skin layer and space layer, respectively. Lastly, the cumulative differences in renovated GFA from the monolithic model are presented in Fig. 5, e and f. The differences in renovated GFA values for SF and MF buildings in Year 2050 are 44 million m^2 and 30 million m^2, respectively. To place these numbers in context, the differences represent 14% and 15% of the total GFA for SF and MF buildings, respectively.

5.4 Sensitivity analysis

In this section, we test how sensitivity the LRM is to different lifetime parameters. We only vary the renovation cycles,

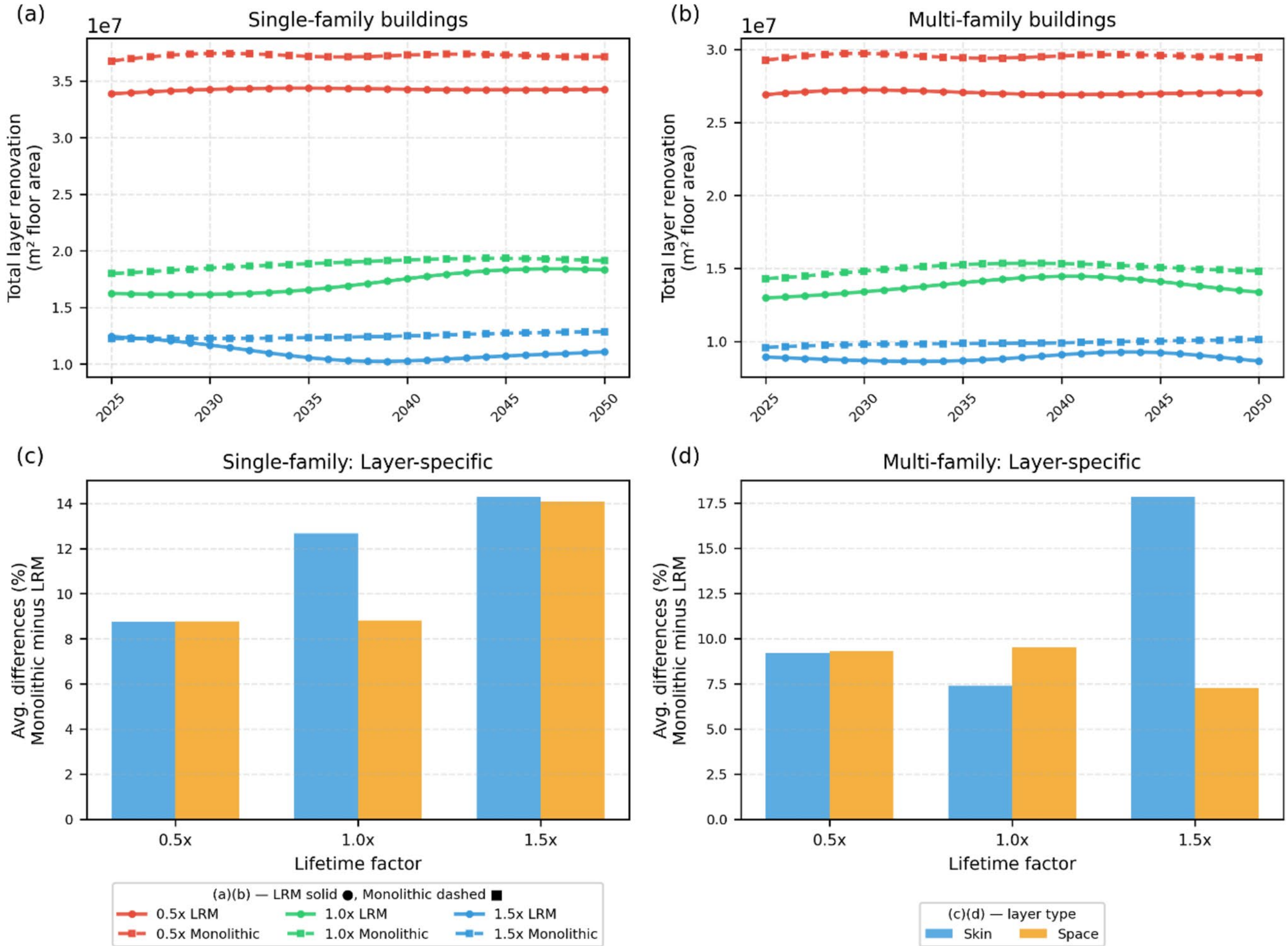


Fig. 6 Sensitivity analysis of the inflows of floor area from renovation activities between the monolithic and LRM for the baseline and varied layer lifetime factor for the mean lifetime (**a** and **b**), and the average differences of the renovations for each sensitivity scenario. The data for Fig. 6 can be found in Supplementary Information SI1

and we do not vary the lifetime distribution as the results from Miatto et al., (2017) suggests that parameters have much larger impact on results. We scale the mean parameter of the lifetime distribution by 50% and 150% to simulate faster and slower renovation cycles respectively, as shown in Fig. 6. In the low or 50% scenario, the mean parameters for skin and space layer are 17.5 years and 12.5 years. While in the high or 150% scenario, the mean parameters for skin and space layer are 52.5 years and 37.5 years

The total amounts of renovated floor space are shown in Fig. 6 (a and b). As expected, the low scenario with lower mean lifetime leads to more frequent renovations, where the cumulative differences in renovated floor area are 77 million m^2 and 65 million m^2 for SF and MF buildings respectively. On the other hand, the high scenario with higher mean lifetime leads to less frequent renovations, where the cumulative differences in renovated floor area are 37 million m^2 and 25 million m^2 for SF and MF buildings respectively. The results show that for all years and all scenarios the monolithic model yields higher renovated floor area besides in the year 2025 and 2026 for single-family buildings, with the differences being 177,702 m^2 and 67,842 m^2 respectively. We can conclude based on these results that the hypothesis of the monolithic model yielding more renovated floor area holds true for most scenarios and years. The average differences in renovated floor area for each scenario are shown in Fig. 6 (c and d). The average differences for SF buildings are more similar for the skin and space layer, with the averages being 8.8% and 8.8% in the low scenario and 14.3% and 14.1% in the high scenario. The average differences for MF buildings, however, are more different, with the averages being 9.2% and 9.3% in the low scenario and 17.8% and 7.3% in the high scenario. We can conclude that the averages differences in renovated floor area between the LRM and monolithic model varies between layers depending on the chosen mean lifetime, but the result that monolithic model yields higher estimates holds true in both scenarios.

In addition, we tested how sensitivity the LRM is to structural lifetime, as shown in Fig. 7(a, b) in absolute values and average percentage differences in Fig. 7(c, d).

The results show that in general the choice of structural lifetime has very minimal impact on the model output. The structural lifetime parameters do not affect the total renovated floor area of the monolithic model as the renovation activities are independent from the structural lifetime. Some differences are observed in the LRM model when structural lifetime is varied. In the 75% baseline lifetime scenario, the difference is 14,000 m^2 for SF and 16,000 m^2 for MF buildings, which represents a 0.1% difference. In the 125% baseline lifetime scenario, the differences are even smaller, at 5000 m^2 for SF and 5800 m^2 for MF. In terms of layer specific result, the average differences in the baseline scenario between LRM and monolithic is 12.7% for the skin layer and 8.8% for the space layer for SF buildings, and 7.4% for the skin layer and 9.5% for the space layer for MF buildings. In both the 75% and 125% baseline lifetime scenarios, the average differences remain almost identical, while the average differences for the skin layer reduces to 12.4% and 7.2% for SF buildings in the 75% baseline lifetime scenario and increases to 12.8% and 7.5% for MF buildings in the 125% baseline lifetime scenario. The result of this sensitivity analysis shows that the structural lifetime does not have a large impact on the model output but also highlights the contribution of the LRM by modeling renovation activities as dependent on the structural lifetime.

6 Discussion

6.1 Lifetime and renovation assumptions

The structural lifetimes of buildings have strong impacts on the material results from dynamic building stock MFA models (Cao et al., 2019; Hingorani et al., 2023). Structural lifetimes are used to model the demolition of buildings, and

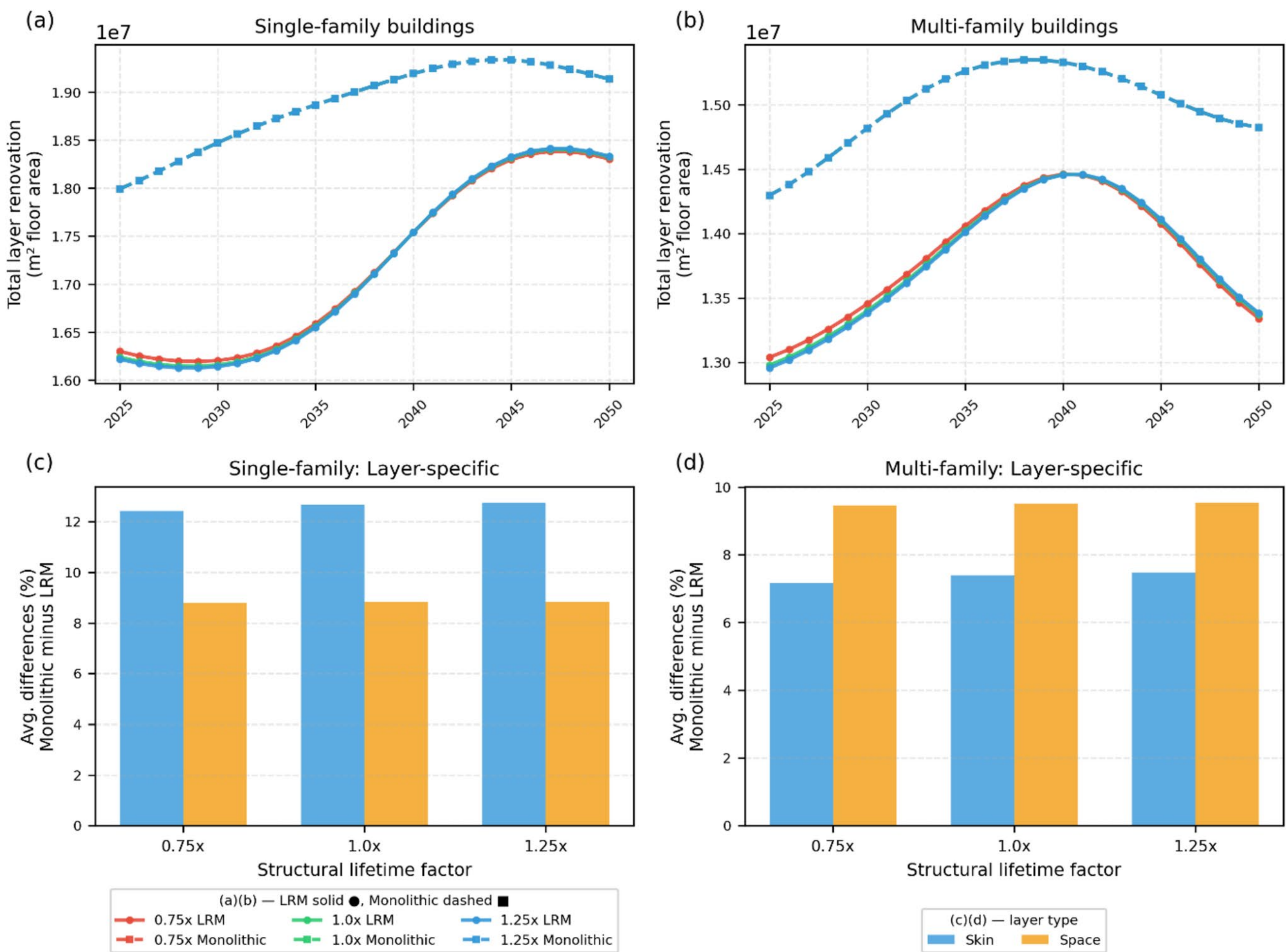


Fig. 7 Sensitivity analysis of the inflows of floor area from renovation activities between the monolithic and LRM for the baseline and varied structural lifetime factor for the mean lifetime (**a** and **b**), and the average differences of the renovations for each sensitivity scenario. The data for Fig. 7 can be found in Supplementary Information SI1

these lifetimes can be highly variable across different countries, being influenced by more than the physical aspects related to deterioration (Diamantidis et al., 2018). There are no official demolition rate data published in Sweden in terms of the amount of floor area being demolished per year. We assume a mean lifetime of 300 years to simulate a demolition rate of about 0.05%. This matches the demolition rate calculated for MF buildings by dividing the number of MF buildings demolished per year by the total number of MF buildings in Sweden. The mean lifetime of 300 years is higher than the estimate for most other countries, including Denmark, where the mean lifetime of residential buildings is estimated to be 120 years (Andersen & Negendahl, 2023). The exception is the lifetime calculated for the city of Padua in Italy, which is as high as 962 years for buildings constructed between 1902 and 1954 (Miatto et al., 2019). This does not have a significant impact on the main findings of the study, although it does highlight that greater efforts are needed to collect lifetime data. Furthermore, a systematic review and comparison of building lifetimes will be very useful to the community.

We follow a similar approach to that adopted by Sartori et al., (2016) in using a renovation cycle with lifetimes that follow a normal distribution to simulate renovation activities. However, this may not represent how renovation activities are carried out in reality. Renovation activities are highly sensitive to cost, and not just the physical lifetime of the façade or insulation. Furthermore, there are no complete data detailing when each building was last renovated in Sweden, so we are assuming that each building will go through cycles of renovations until demolition. This aspect will be improved when accurate renovation data becomes available. A comprehensive analysis of building renovation frequencies will also be beneficial. Lastly, we do not assume that renovation activities will extend the lifetimes of buildings in the current model. This can be incorporated into the model if more-accurate lifetime and renovation frequency data become available, that represents renovation activities more accurately. We believe that with the inherent uncertainties associated with lifetimes, the difference in results is negligible.

6.2 Validation of the results

In this section, we compare our results with those of previous studies to validate the results. In a previous study, Gontia et al. (2020) estimated the material stock and flows of the Swedish residential building stock. In Gontia et al. (2020), the authors use top-down data from Statistics Sweden and the material intensities used are also less refined. The total MS according to Gontia et al. (2020) is 438 Mt, while the total MS in the present work is 354 Mt. This can largely be explained by the differences in MI, as well as the difference in building inventories in terms of floor area.

6.3 Implications of results

The findings have important implications for renovation-centered climate strategies. The main contribution of this study is to introduce layers into dMFA model of building renovation, and the main advantage of the LRM is the policy implications. As shown in Gobbo et al., (2024), material outflows from different layer have significantly different circularity potentials, ranging from 1%—5% in mass for the structure layer to 10—25% in mass for the space layer. The LRM can be further developed to include circularity assessment potential, and the model will be particularly relevant for policy makers as the model can be modeled from urban to national scales. Furthermore, separating buildings into layers also enables more detailed modeling of energy efficiency renovation, as such renovations happen in different layers, for example wall and window renovation in the skin layer and roof and floor renovation in the structure layer (Ma et al., 2025). In addition, circularity measures could also significantly offset the embodied emissions from renovations (Zhang et al., 2025). In the future, we plan on expanding the model to cover both the circularity potential and embodied emission from building renovations.

However, introducing additional dimensions also introduces more uncertainties to the model (Puy et al., 2022). The trade-off between the additional uncertainties and the ability to model multiple layers depends on the objective and research question. The LRM is more appropriate for when the temporal dynamic of material flow for each layer is important, such as modeling energy efficiency renovations, or when assessing circularity potential. The monolithic approach is more appropriate for cases where certainty is more relevant than granularity, for example in retrospective analysis. The LRM should also be applied to other geographical regions to validate its robustness.

7 Conclusions

Buildings are systems of layers and components instead of homogeneous units and should be modeled as such in dMFA studies. In this study we introduced a layer renovation model based on the concept of shearing layers to model renovation activities. We demonstrated the framework using residential buildings in Sweden as case study. We utilized a set of layer-specific material intensity data to calculate the material stock and modeled the material flows from renovation activities. The results from the LRM are compared with the results from the traditional monolithic model.

This study highlights the traditional monolithic model used in most existing dMFA studies result in higher amount of renovated floor area, by 12.6% and 8.8% for the skin and space layer compared to the proposed LRM, respectively. The main driver for the differences in results is the LRM treating the lifetimes of the skin and space layer that represents renovation probability as correlated with the structural lifetime that represents demolition, instead of treating these lifetimes as independent. We present the LRM as an alternative dMFA approach for modeling building renovations for cases where the material intensity data allows for the building stock to be treated as a system of layers or components.

For future work, the LRM should be applied and tested in other geographical areas to validate the robustness and transferability of the results. In addition, the model can be expanded to answer questions such as embodied carbon or circularity potential of building renovations. The model could be particularly for circularity related research questions, as tracking the material flow dynamics of structural and non-structural components is crucial for such studies.

8 Summaries

Supplementary Information S1: This supporting information provides the data used in the main article for Figures 2 to 7.

Supplementary Information S2: This supporting information provides an overview of the method as well as data on material intensity and emission factors used in the main article.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s44498-026-00164-3.

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Author contributions Qiyu Liu: Writing—original draft, Visualization, Software, Methodology, Conceptualization. Maud Lanau: Writing – review & editing, Supervision, Data Acquisition, Methodology, Conceptualization. Johan Rootzén: Writing – review & editing, Supervision, Project administration, Funding acquisition. Zhi Cao: Writing – review & editing, Methodology. Filip Johnson: Writing – review & editing, Supervision, Funding acquisition.

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Data availability Data will be available on request.

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