

From Urban Growth to Material Accumulation: Reconstructing Building Stock Dynamics in Gothenburg, from 1960 to 2015

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Research Article

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From Urban Growth to Material Accumulation: Reconstructing Building Stock Dynamics in Gothenburg, from 1960 to 2015

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Abstract

Urban building stocks accumulate large quantities of materials, but their long-term development is difficult to reconstruct at the building level because historical inventories often lack consistent information on building attributes and turnover. This study develops a spatially and temporally explicit framework for reconstructing building-stock dynamics and associated material flows by integrating historical GIS, building morphology, street-network characteristics, and machine-learning-based attribute enrichment. The framework is applied to Gothenburg, Sweden, from 1960 to 2015. Successive historical building layers are compared to identify construction and demolition, while missing information on building function and residential structural typology is inferred using machine-learning models. The reconstructed attributes are combined with gross floor area and material-intensity coefficients to quantify residential material stocks, construction inflows, and demolition outflows. Over the study period, Gothenburg's population increased by 29%, while residential gross floor area increased by 102% and the estimated residential material stock by 39%. Approximately 10.9 Mt of residential materials entered the stock through new construction, while 1.14 Mt were released through identified demolition, resulting in approximately 9.75 Mt of net material accumulation. Construction and material inflows were concentrated in the late 1960s and early 1970s and were distributed unevenly across the city. Contemporary population density was positively associated with cumulative material-inflow density but explained only part of its spatial variation. The study demonstrates how historical spatial data and machine learning can support building-level reconstruction of long-term stock dynamics, providing an empirical basis for analysing the spatial formation, persistence, and turnover of urban material stocks.

Keywords

Urban material stocks; Building stock dynamics; Material flows; Construction and demolition; Historical GIS; Machine learning; Urban morphology; Urban metabolism; Gothenburg; Spatio-temporal reconstruction

1. Introduction

Cities are complex, open systems that continuously exchange materials, energy, and other resources with their surroundings. Understanding these exchanges is central to developing more sustainable cities (Kennedy & Hoorweg, 2012). The concept of urban metabolism (UM) describes cities in terms of resource inputs, transformations, stocks, and outputs (Newman, 1999; Wolman, 1965; Zhang, 2013), while material flow analysis (MFA) quantifies the materials entering, accumulating within, and leaving socioeconomic systems (Brunner & Rechberger, 2003). Urban metabolism cannot, however, be understood from annual flows alone. Buildings and infrastructure retain materials for decades or centuries, linking past resource use and urban development to future waste generation and opportunities for material recovery. The built environment therefore represents both a major component of urban metabolism and a material record of past urban development.

The scale of this accumulation is substantial. Global socioeconomic material stocks increased approximately 23-fold between 1900 and 2010, reaching about 792 Gt, while roughly half of annual material extraction was used to build or renew these stocks (Krausmann et al., 2017). Buildings and infrastructure consequently constitute major reservoirs of anthropogenic materials and potential sources of future demolition waste and secondary resources. Built-environment stocks also create spatial and temporal lock-ins but remain unevenly represented across building types, spatial scales, and historical periods (Lanau et al., 2019; Rosado et al., 2017). Urban metabolism research has therefore expanded from analysing material throughput towards examining the quantity, composition, location, and temporal development of material stocks.

Building stocks are not static repositories of materials but evolving systems shaped by construction, persistence, transformation, and demolition (Kohler & Hassler, 2002). Materials enter the built environment through construction, remain embedded throughout the service lives of buildings, and may eventually reappear as demolition outflows. Material stocks observed at a particular time are therefore cumulative outcomes of previous inflows, outflows, and building persistence. Understanding urban material metabolism consequently requires not only estimating the materials stored within cities but also reconstructing the processes through which those stocks developed.

Dynamic material-stock and flow models have addressed these processes by relating stock accumulation to population, floor-area demand, economic activity, and changing service requirements. Stock-driven approaches derive construction, and demolition flows from changes in desired stock levels and assumptions about building lifetimes (B. Müller, 2006; Hu et al., 2010). Such models are valuable for analysing long-term trajectories and prospective material demand, but their representation of turnover is sensitive to assumptions about building lifetimes and mortality. Empirical studies have shown that demolition is not determined by age alone and that alternative lifetime assumptions can substantially alter estimates of material outflows and demolition waste (Aksözen et al., 2017; Cord'homme et al., 2025; Miatto et al., 2017). Empirical evidence on when and where buildings are constructed, retained, and demolished is therefore important for understanding and modelling building-stock dynamics.

Bottom-up and spatially explicit material-stock analyses provide a complementary perspective. These approaches combine building inventories with information on geometry, floor area, construction period, function, and structural characteristics and apply material-intensity

coefficients to estimate material quantities at the building or neighbourhood scale (Arbabi et al., 2022; Heeren & Hellweg, 2019; Kleemann et al., 2017; Tanikawa & Hashimoto, 2009). They have improved understanding of the spatial distribution of urban materials and their implications for demolition waste, urban mining, and circular-economy strategies. Their reliability, however, depends on the quality and completeness of building-level information. Historical inventories frequently lack attributes required for material classification, while construction and demolition are often inferred rather than directly identified.

Historical reconstruction can address part of this limitation by deriving stock dynamics from observed changes in the built environment. Four-dimensional GIS demonstrated the potential to trace urban material stocks through space and time (Tanikawa & Hashimoto, 2009). Subsequent studies combined historical maps, aerial photographs, cadastral information, and building records to reconstruct urban development. Aksözen et al., (2017), for example, reconstructed more than 60,000 buildings over 180 years to analyse building survival and demolition, while Miatto et al., (2019) reconstructed material accumulation and demolition-waste potential in Padua. These studies demonstrate the value of historical evidence for analysing turnover but also reveal a persistent limitation: historical datasets often lack building function, structural characteristics, and other information required for detailed material accounting.

Machine-learning methods offer opportunities to address these data gaps. Building attributes are related to observable characteristics of buildings and their spatial context, including geometry, density, accessibility, and location. Morphological and contextual indicators can therefore provide predictive information about building functions and structural systems relevant to material-stock estimation. Bian et al., (2026) for example, showed that morphological indicators could predict residential structural typologies in Gothenburg, with important implications for estimated material quantities. Data-driven attribute enrichment can thus extend material-stock analysis to historical periods for which complete building information is unavailable.

Material accumulation is also inherently spatial. Population growth does not necessarily produce proportional growth in floor area or material stocks, and previous studies have identified substantial spatial and temporal differences in material accumulation among cities and regions (Gontia et al., 2020; Schug et al., 2023). These differences are embedded in urban structures composed of streets, plots, and buildings that persist and change at different rates (Berghauser Pont et al., 2019; Bobkova et al., 2021) (Berghauser Pont et al., 2019; Bobkova et al., 2021). Plots are particularly relevant because they connect the physical division of land with property and control and provide an organisational framework for the evolution of built form (Kropf, 2018; Bobkova et al., 2021). Their size, frontage, and configuration can enable or constrain intensification, replacement, and redevelopment, thereby influencing the conditions under which building stocks evolve (Tümtürk et al., 2025). Patterns of material accumulation and turnover may therefore reflect not only demographic and economic change but also the spatial and institutional structures through which urban development occurs.

Recent research has begun to connect urban morphology and building-stock metabolism. Kolkwitz et al., (2023), for example, showed how construction, demolition, and replacement can be understood as spatially differentiated components of urban material flows. Nevertheless, the relevant research traditions remain only partly integrated. Material-stock studies quantify the magnitude and distribution of urban materials, historical GIS reconstructs building-stock change, and urban morphology examines the spatial organisation of urban transformation. Relatively few studies integrate observed turnover, historical attribute enrichment, and material accounting within a common building-level framework spanning multiple historical periods.

This study addresses this gap through a building-level reconstruction of Gothenburg's building stock between 1960 and 2015. Successive historical building and street-network layers are used to identify construction and demolition and to characterise the morphological and spatial contexts of individual buildings. Machine-learning models infer building function and residential structural typology where historical information is unavailable. These reconstructed attributes are combined with gross floor area and material-intensity coefficients to estimate residential material stocks and the material inflows and outflows associated with construction and demolition.

By integrating historical GIS, machine learning, urban morphology, and material-stock accounting, the study reconstructs how urban growth translated into material accumulation over more than five decades. The approach distinguishes material stocks from the construction inflows and demolition outflows through which they change while retaining the spatial and temporal attributes of individual buildings. It thereby provides an empirical framework for analysing long-term building-stock dynamics and their relationships with population concentration, building characteristics, and urban spatial structure.

1.1. Aim and research questions

The aim of this study is to reconstruct the spatial and temporal evolution of Gothenburg's building stock between 1960 and 2015 and to examine how building-stock dynamics relate to the accumulation and turnover of residential materials.

The study addresses the following research questions:

- How did Gothenburg's building stock evolve spatially and temporally between 1960 and 2015, and where were building construction and demolition concentrated?
- How are spatial patterns of residential material accumulation and turnover related to population density, building characteristics, and urban spatial structure?

2. Data and methods

2.1. Data

The analysis uses the *GIS-based Time Model of Gothenburg, 1960–2015*, which provides historical building and street-network layers at five-year intervals (Stavroulaki et al., 2025). The dataset was developed to document changes in Gothenburg's spatial structure over time and comprises 12 historical representations of the city's buildings and street network. Details of the dataset reconstruction, source material, and quality-control procedures are provided in the dataset documentation. The building layers contain individual building polygons with information on construction year, footprint area, gross floor area (GFA), height, and number of floors.

Geometric and morphological indicators were derived from the building polygons and combined with network-based measures describing accessibility and urban spatial structure. These variables were calculated for each historical period using the corresponding building and street-network layers, ensuring temporal consistency between buildings and their surrounding urban context. More information on these variables is available in Supplementary Material 1.

Contemporary building data were used as labelled observations for building-function classification, while a labelled sample of residential buildings was used to train the residential

structural-typology model (Bian et al., 2026). Material-intensity coefficients were obtained from Gontia et al., (2019). Population data for 2015 were obtained from Statistics Sweden at the level of Demographic Statistical Areas (DeSO) and used to calculate population density. A complete description of the datasets, derived variables, and sources used in the present analysis is provided in Supplementary Material 1.

2.2. Reconstruction of the building and material stocks

The reconstruction followed a sequential building-level framework comprising four main steps (Figure 1). Step 1 involved training two classification models: one for residential structural typology and one for building function. Step 2 identified construction and demolition by comparing consecutive historical building layers. In Step 3, the trained models were applied to the historical building stock to reconstruct missing building attributes. Step 4 combined the classified residential buildings with material-intensity coefficients to quantify residential material stocks and flows.

Geometric, morphological, and street-network predictors were calculated before model training and historical prediction. For historical buildings, predictors were calculated using the building and street-network layers corresponding to the same period. A detailed data-flow diagram is provided in Supplementary Material 1, Figure A1.

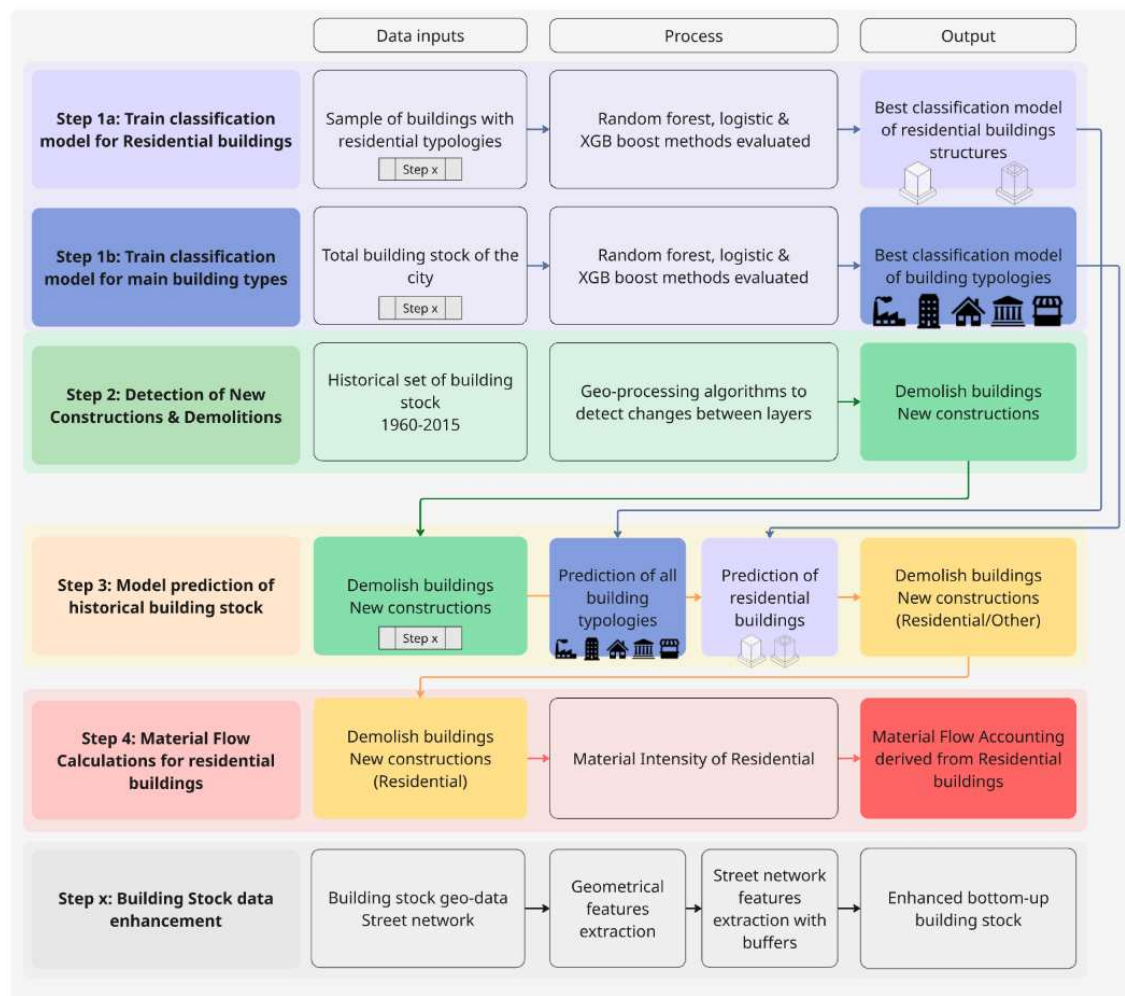


Figure 1. Methodological framework for the reconstruction of Gothenburg's building stock and residential material stocks and flows.

Step 1a: Training the residential structural-typology model

The residential structural-typology model was trained using a labelled dataset of 331 residential buildings from Bian et al., (2026). The sample comprised four structural typologies: CMF (111 buildings), MMF (78), WBMF (73), and WMF (69). WSF buildings were excluded from this model because of the insufficient number of labelled observations. Instead, WSF buildings were identified through the single-family residential class generated by the building-function model in Step 1b.

Building morphology and spatial-context variables were used as predictors. Random Forest, Ranger Random Forest, and XGBoost classifiers were initially compared. Ranger and XGBoost were subsequently evaluated using repeated five-fold cross-validation with three repeats and hyperparameter optimisation. Model selection was based on cross-validated accuracy rather than performance on the independent holdout set.

XGBoost achieved the highest cross-validated accuracy, at 86.0%, and was selected as the final classifier. The model used 71 predictors and 100 boosting rounds. On the independent holdout set, it achieved an accuracy of 88.9% and a Cohen's kappa of 0.851. Model configurations, feature selection, hyperparameter optimisation, and confusion matrices are reported in Supplementary Material 2.

The trained model was retained for application in Step 3 to historical buildings classified as multifamily residential. The resulting structural-typology predictions were used to assign material-intensity coefficients in Step 4.

Step 1b: Training the building-function model

The building-function model was trained using contemporary labelled building data. The original classification comprised seven categories: Residential, Commercial, Industrial, Public Service, Farm Building, Accessory Building, and Other Building. For the historical reconstruction, these categories were consolidated into six functional groups: single-family residential, multifamily residential, commercial, industrial, institutional, and auxiliary.

Building function was predicted from 66 morphological and spatial-context variables describing building size and geometry, location, and characteristics of the surrounding street network. The labelled dataset contained 166,346 buildings, of which 133,080 were used for model training and 33,266 for independent testing. Random Forest and XGBoost classifiers were evaluated using cross-validation and subsequently assessed on the independent test set.

XGBoost achieved the highest cross-validated accuracy, at 88.7%, and was selected as the final classifier. On the independent test set, it achieved an accuracy of 88.8% and a Cohen's kappa of 0.804. Model specifications, hyperparameter optimisation, and confusion matrices are provided in Supplementary Material 2.

The trained model was retained for application to the historical building layers in Step 3. Its predictions were used to distinguish single-family and multifamily residential buildings from commercial, industrial, institutional, and auxiliary buildings.

Step 2: Detection of construction and demolition

Construction and demolition were identified by comparing consecutive historical building layers at five-year intervals. Buildings present in an earlier layer but absent from the subsequent layer

were identified as demolished, while buildings absent from the earlier layer but present in the subsequent layer were identified as newly constructed.

Buildings present in both consecutive layers were retained as part of the persisting stock. This procedure generated a spatially explicit record of building additions, removals, and persistence between 1960 and 2015. Construction and demolition were identified from changes in the historical building layers independently of the building classifications developed in Step 1.

Step 3: Attribute prediction for the historical building stock

The models trained in Steps 1a and 1b were applied to the historical building layers. The building-function model was first used to classify buildings as single-family residential, multifamily residential, commercial, industrial, institutional, or auxiliary. Single-family residential buildings were subsequently assigned to the WSF structural typology, while the residential structural-typology model was applied to buildings classified as multifamily residential.

Predictors for each historical building were derived from the building and street-network layers corresponding to the same period. Model predictions therefore reflected the spatial context in which each building existed rather than its relationship to the contemporary urban network.

The resulting building-level inventory contains building geometry and physical characteristics together with predicted function and, for residential buildings, structural typology. The inventory represents the buildings present in each historical period and identifies buildings entering the stock through construction, leaving through demolition, or persisting between periods. It formed the basis for the residential material calculations in Step 4.

Step 4: Residential material-stock and flow calculation

Residential material stocks were quantified by combining the GFA of each residential building with structural-typology-specific material-intensity coefficients from Gontia et al., (2018). The resulting estimates represent the quantities of individual materials embodied in each building.

Material inflows were calculated from the material quantities assigned to newly constructed residential buildings, while material outflows were calculated from those assigned to demolished residential buildings. Net material accumulation was determined as the difference between construction inflows and demolition outflows for each period.

Because these calculations were performed at the building level, the resulting material stocks and flows retained their spatial allocation. They could therefore be aggregated by period, location, structural typology, and material category and analysed in relation to population density, building characteristics, and urban spatial structure.

2.3. Spatial and statistical analysis

Building-stock changes and associated material flows were summarised by five-year period, building function, residential structural typology, and material category. Spatial patterns were examined using building-level maps, kernel-density estimates of constructed and demolished building area, and distance-based distributions relative to Gothenburg Central Station.

For the population analysis, building-level residential material inflows for 1960–2015 were aggregated to Demographic Statistical Areas (DeSO) and divided by area to calculate cumulative

material-inflow density. This measure and 2015 population density were log-transformed. Ordinary least-squares regression estimated their average spatial association, while conditional quantile regression examined variation across the distribution of material-inflow density. These relationships were interpreted as spatial associations rather than causal effects.

Material composition and its temporal development were examined by aggregating residential inflows and outflows by material category and five-year period.

3. Results

3.1. Evolution of the reconstructed building stock

Comparison of consecutive historical layers identified 39,685 newly constructed buildings and 950 demolished buildings between 1960 and 2015, corresponding to approximately 13.6 km² of added footprint and 0.85 km² of removed footprint. Figure 2a presents examples of detected additions and removals, while Figure 2b shows their spatial concentration based on constructed and demolished building area. Period-specific maps are provided in Supplementary Material 3.

Construction and demolition were concentrated in the historic urban core and around Gothenburg Central Station. Additional concentrations of construction occurred in Angered and Gunnared, Västra Frölunda and the area surrounding Frölunda Torg, Torslanda, and other parts of Hisingen.

Residential buildings accounted for 33,491 additions and 6.35 km² of newly constructed footprint. The remaining additions comprised 3,023 auxiliary buildings covering 0.65 km², 1,830 industrial buildings covering 3.62 km², 736 institutional buildings covering 1.96 km², and 605 commercial buildings covering 1.07 km². Among the demolished buildings, 613 were residential, accounting for 0.39 km² of removed footprint. Commercial buildings accounted for 130 demolitions and 0.19 km², auxiliary buildings for 93 demolitions and 0.02 km², industrial buildings for 63 demolitions and 0.18 km², and institutional buildings for 51 demolitions and 0.07 km². See Table 1, in Appendix detailed results.

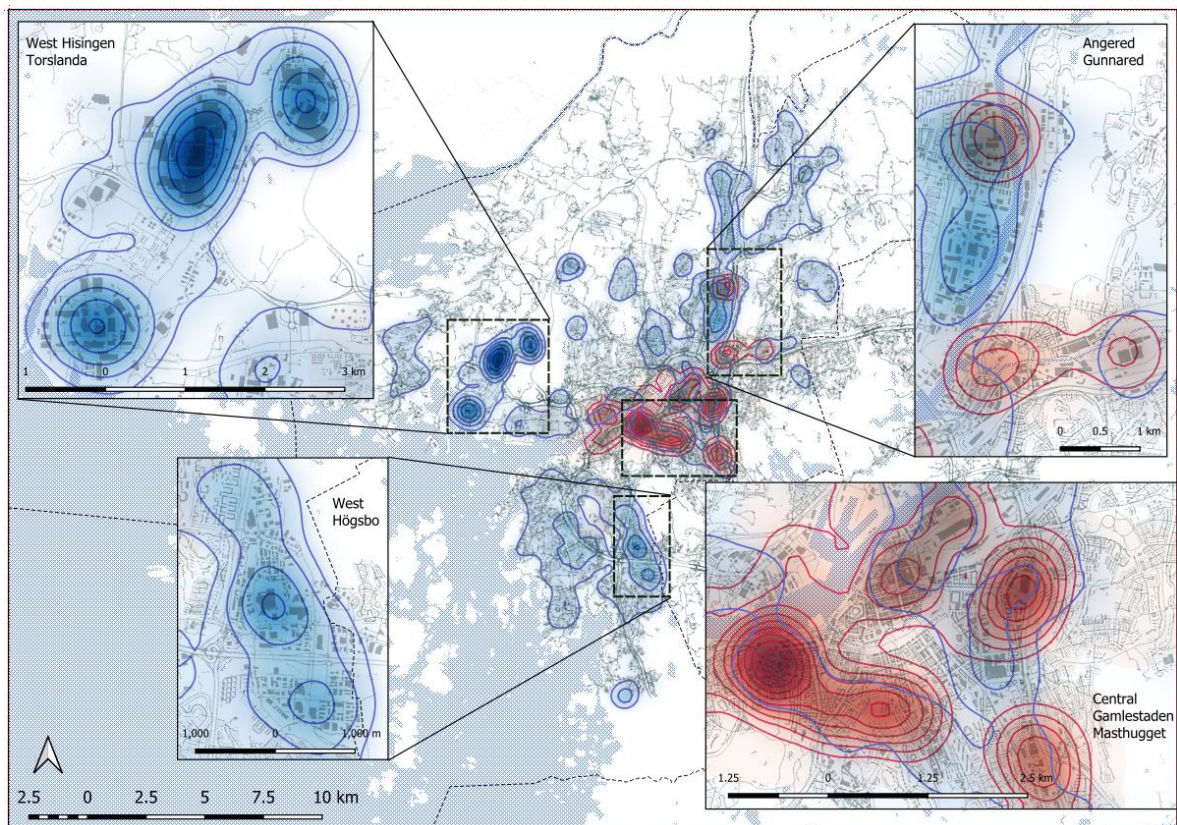
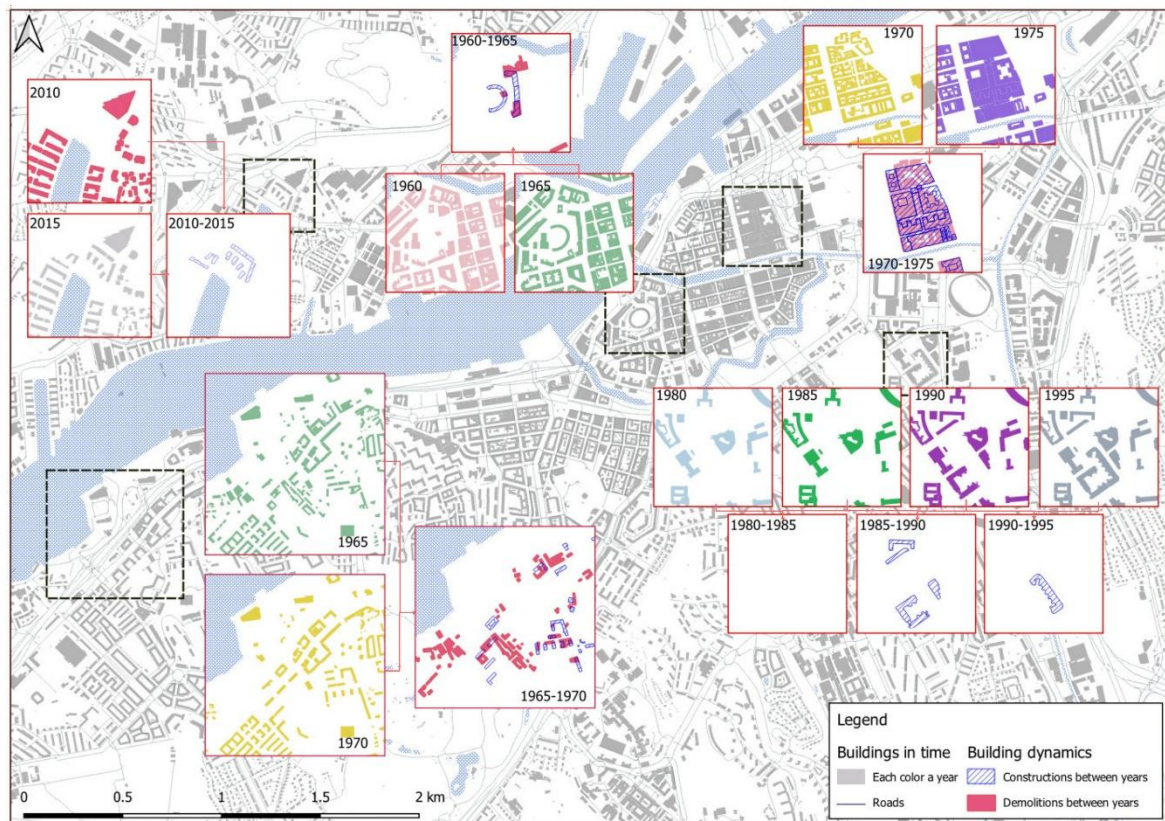


Figure 2. Spatial distribution of detected building construction and demolition in Gothenburg between 1960 and 2015. (a) Examples of detected building additions and removals in selected areas; (b) kernel-density estimates of construction and demolition based on added and removed building area.

Construction and demolition varied over time and among building functions (Figure 3a–b). Demolition was concentrated in the earlier periods and declined thereafter. Residential buildings accounted for most demolished buildings, while industrial, institutional, and commercial buildings contributed comparatively large shares of demolished footprint and GFA relative to their numbers. Few demolitions were identified after 1990.

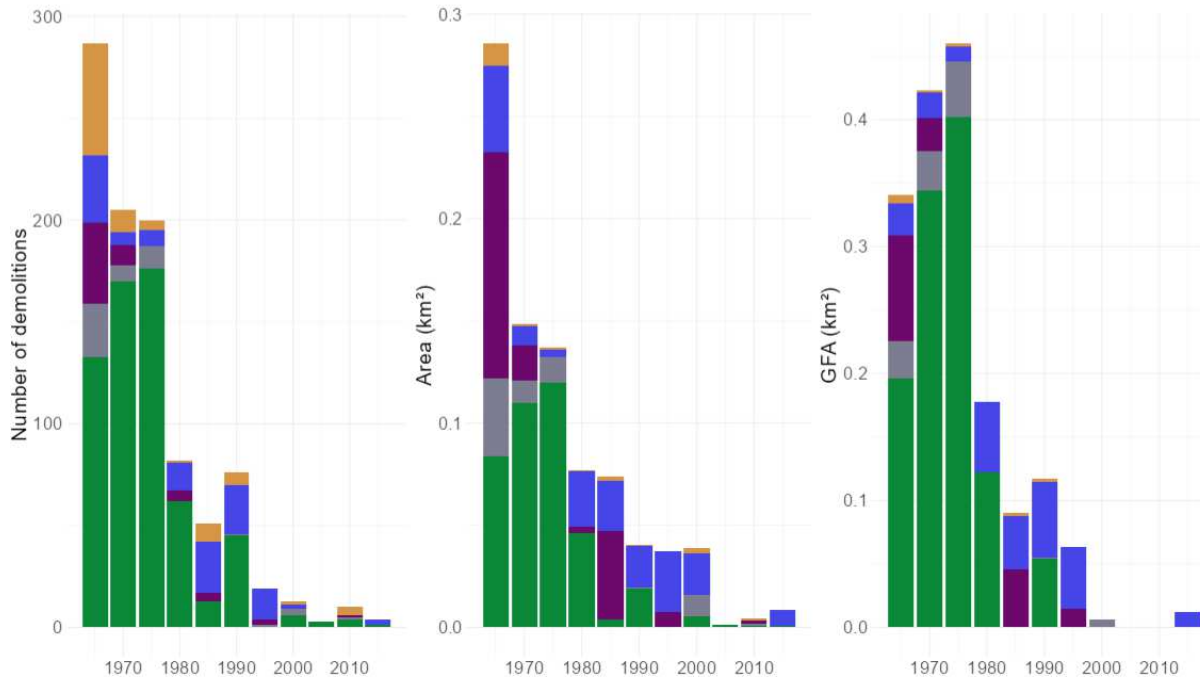
New construction was highest during the late 1960s and early 1970s. The reconstruction identified 5,225 additions in 1965–1970 and 5,853 in 1970–1975. However, newly constructed GFA decreased from approximately 3.57 km² in 1965–1970 to 2.34 km² in 1970–1975. The period with the largest number of additions therefore differed from the period with the largest addition of floor area.

Construction declined during the 1980s and 1990s before increasing during the 2000s when measured by footprint and GFA. The reconstruction identified 2,381 additions in 2000–2005, 2,074 in 2005–2010, and 1,344 in 2010–2015. Residential buildings dominated the number of additions throughout the study period, whereas industrial and institutional buildings contributed comparatively large amounts of constructed footprint and GFA relative to their numbers.

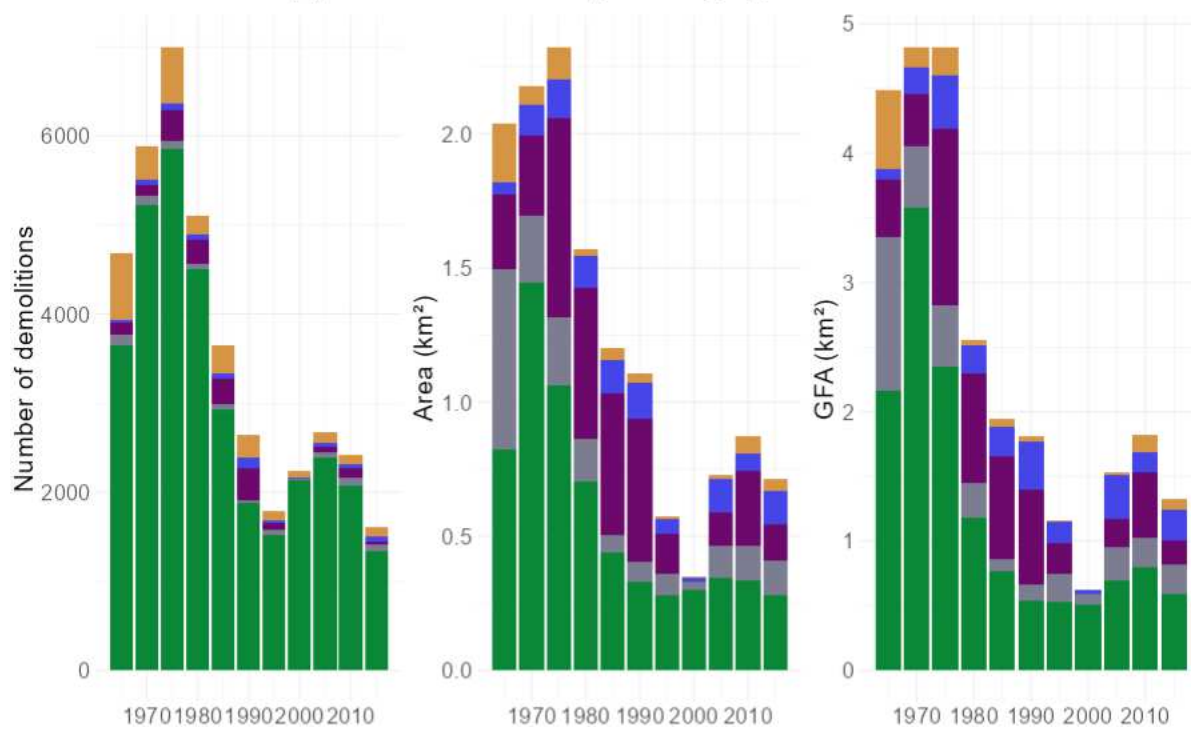
The spatial distribution of newly constructed GFA also varied among building functions (Figure 3c). Residential construction was concentrated primarily between 5 and 10 km from Gothenburg Central Station, with the largest additions at approximately 7–9 km. Commercial construction was concentrated mainly within approximately 5 km, whereas industrial construction exhibited concentrations at approximately 5–7 km and 11–12 km. Residential and industrial construction extended farther from the centre than commercial construction.

The total building footprint increased from approximately 10.8 km² in 1960 to 23.9 km² in 2015, an increase of 121%. Residential footprint increased from 5.8 to 11.7 km², while residential GFA increased from 17.7 to 35.7 km². Both residential measures increased by approximately 102%. Over the same period, Gothenburg's population increased from 443,843 to 572,799 inhabitants, corresponding to an increase of 29%.

(a) Demolitions by Building Type over Time



(b) New constructions by Building Type over Time



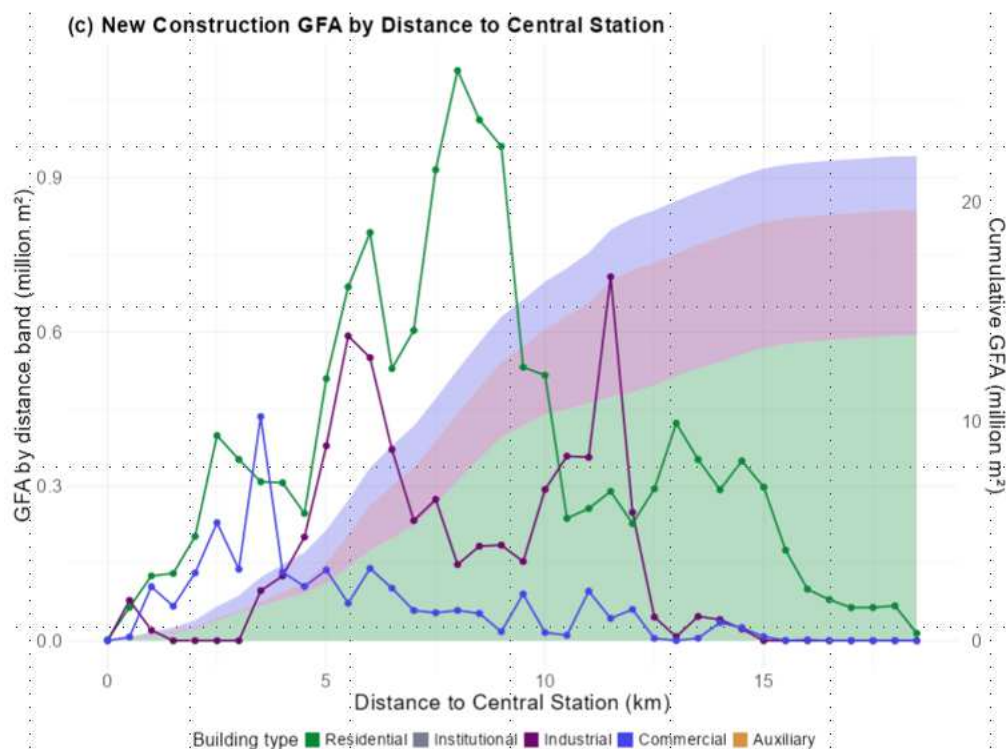


Figure 3. Temporal and spatial patterns of building construction and demolition in Gothenburg between 1960 and 2015. (a) Demolished buildings by period and building function, expressed as building count, footprint area, and gross floor area; (b) newly constructed buildings by period and building function, expressed as building count, footprint area, and gross floor area; and (c) newly constructed gross floor area by distance from Gothenburg Central Station for residential, industrial, and commercial buildings. Lines show gross floor area within each distance band, while shaded areas show cumulative gross floor area with increasing distance from the Central Station.

3.2. Residential material stock and material flows

The estimated residential material stock increased from approximately 24.97 Mt in 1960 to 34.72 Mt in 2015. Approximately 10.89 Mt of residential materials entered the stock through new construction over the study period.

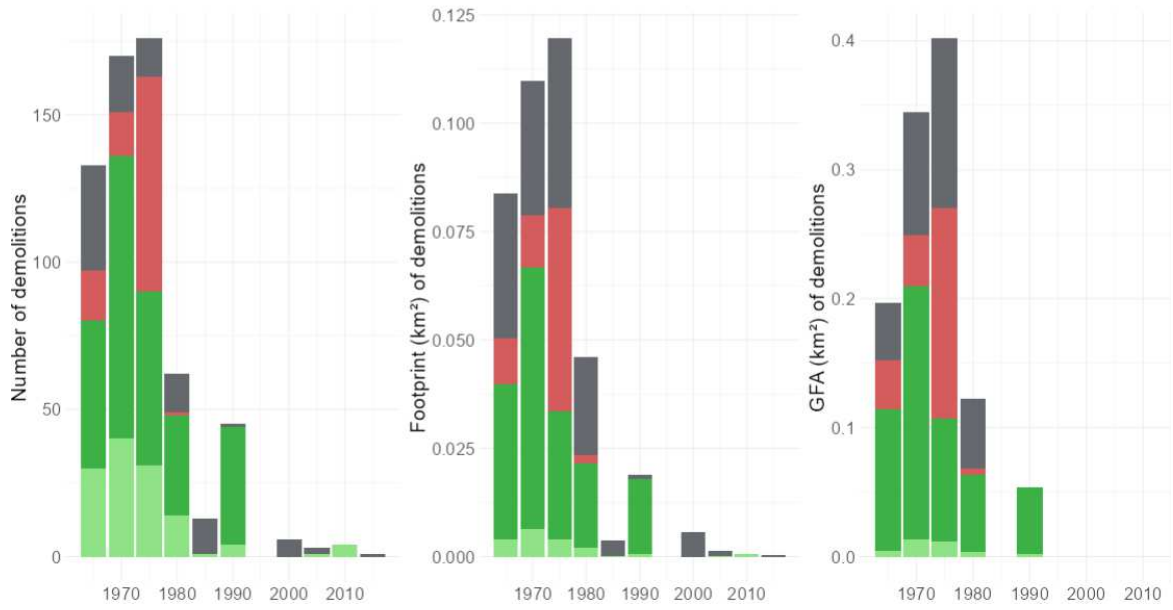
Material inflows were concentrated in the first 15 years of the reconstruction. Approximately 6.84 Mt entered the residential stock between 1960 and 1975, representing 63% of the total construction inflow. The largest five-year inflow occurred in 1965–1970, when approximately 3.28 Mt entered the stock.

The number of residential additions and the associated material inflows followed different temporal patterns. The largest number of additions occurred in 1970–1975, with 5,853 buildings, compared with 5,225 in 1965–1970. However, the associated material inflow decreased from approximately 3.28 Mt in 1965–1970 to 1.90 Mt in 1970–1975.

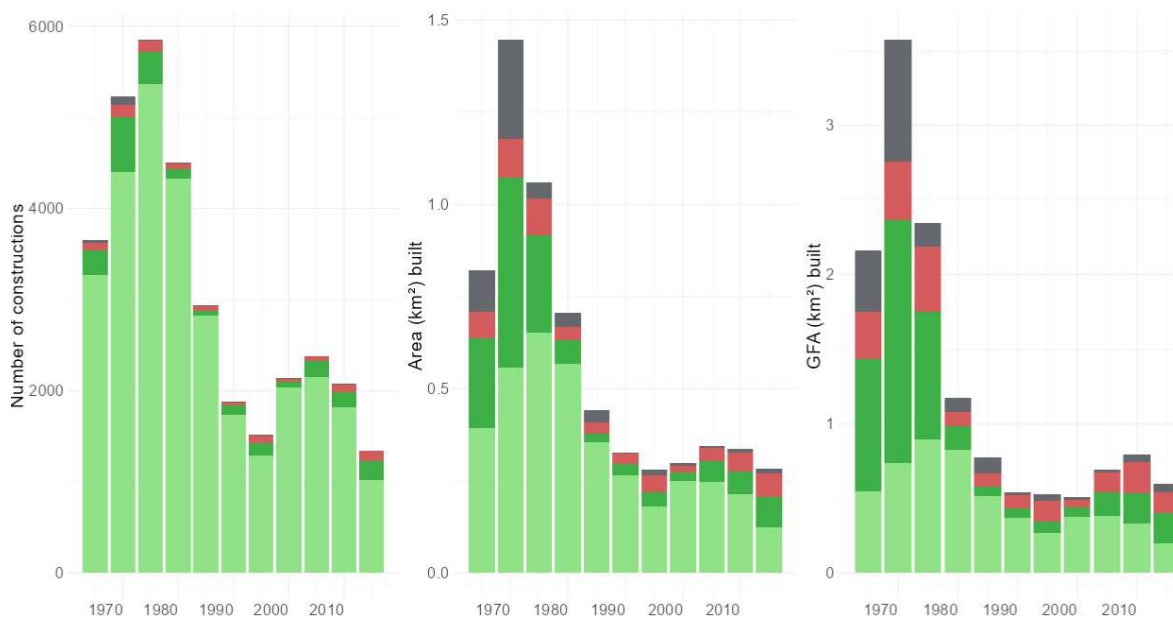
Identified residential demolition generated approximately 1.14 Mt of material outflows. The largest five-year outflow occurred in 1970–1975, when approximately 0.44 Mt was associated with demolished residential buildings. Outflows were substantially lower in subsequent periods, with limited or no identified demolition-related outflows in several later intervals.

Cumulative residential material inflows increased most rapidly during the 1960s and 1970s and continued to increase more gradually thereafter (Figure 4c). WMF buildings contributed the largest share of cumulative construction inflows, followed by CMF, WBMF, and WSF buildings. By 2015, cumulative material inflows from residential construction reached approximately 10.89 Mt.

(a) Residential Demolitions by Structure Type over Time



(b) Residential Construction by Structure Type over Time



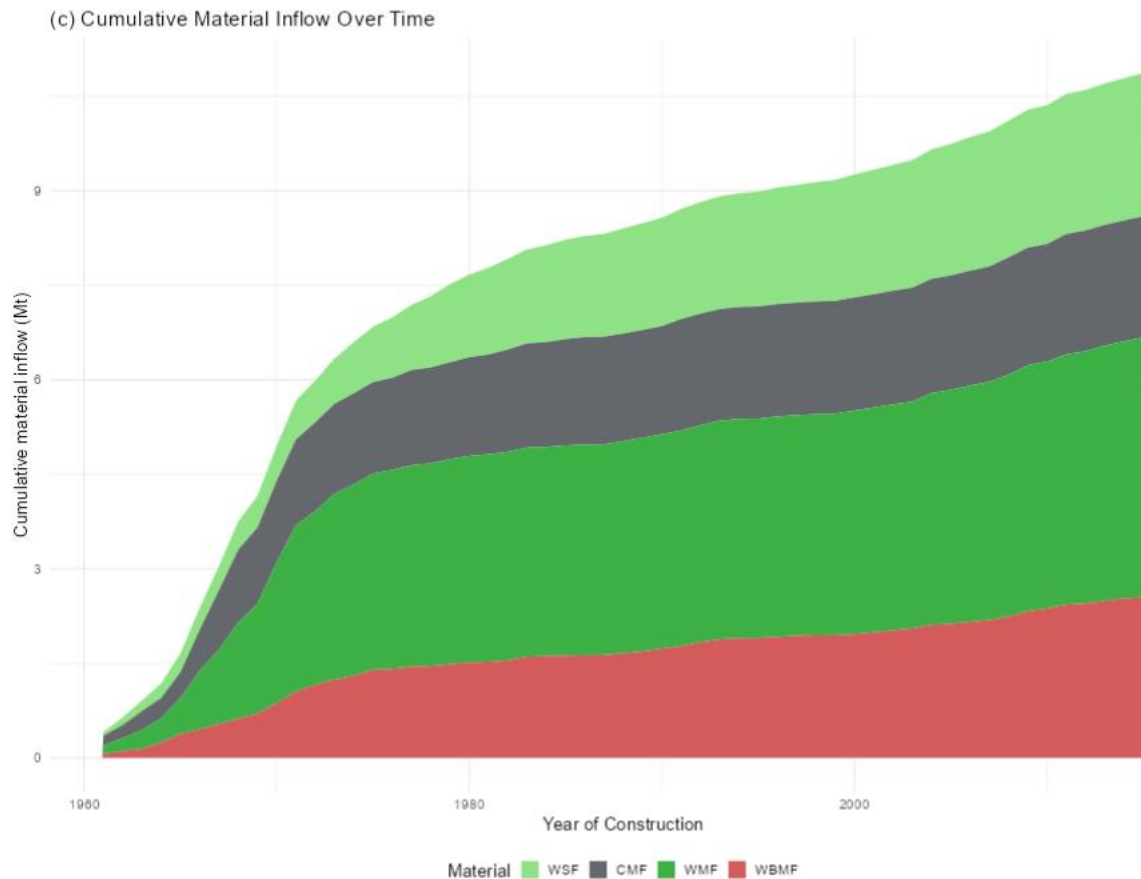


Figure 4. Residential building construction, demolition, and material inflows by structural typology. (a) Demolished residential buildings by five-year period and structural typology, expressed as building count, footprint area, and gross floor area; (b) newly constructed residential buildings by five-year period and structural typology, expressed as building count, footprint area, and gross floor area; and (c) cumulative residential material inflows associated with new construction between 1960 and 2015, disaggregated by structural typology: WSF, CMF, WMF, and WBF.

3.3. Spatial relationship between population density and residential material accumulation

The spatial relationship between population concentration and historical residential construction was examined by comparing 2015 population density with cumulative residential material-inflow density for 1960–2015. Both variables were expressed on logarithmic scales.

The bivariate distribution varied across Gothenburg (Figure 5). Majorna–Stigberget–Masthugget, Krokslätt–Johanneberg, Olivedal–Haga–Annedal–Änggården, and Frölunda Torg–Tofta combined relatively high population density with high cumulative material-inflow density. Parts of Angered, Bergsjön, and Älvsborg contained substantial cumulative material inflows relative to their 2015 population density. Other areas exhibited relatively high population density but lower cumulative material-inflow density.

At the DeSO level, ordinary least-squares regression identified a positive association between population density and cumulative material-inflow density (Figure 5). The estimated coefficient was 0.86 ($SE = 0.058$, $p < 0.001$; $R^2 = 0.439$). In the log-log model, a 10% difference in population density was associated with an estimated 8.6% difference in cumulative material-inflow density.

The estimated association varied across the conditional distribution of material-inflow density. The coefficient was 0.67 at the 10th conditional quantile (95% CI: 0.32–0.82) and 1.04 at the 90th conditional quantile (95% CI: 0.98–1.09).

The positive association was also observed after aggregation to the 23 Mellan sites. The Mellan-level log-log model produced a coefficient of 0.55 ($SE = 0.174$, $p = 0.0047$; $R^2 = 0.323$; adjusted $R^2 = 0.291$). A 10% difference in population density was therefore associated with an estimated 5.5% difference in cumulative material-inflow density at this level of aggregation. The estimated coefficient and explained variance were lower than those obtained at the DeSO level.

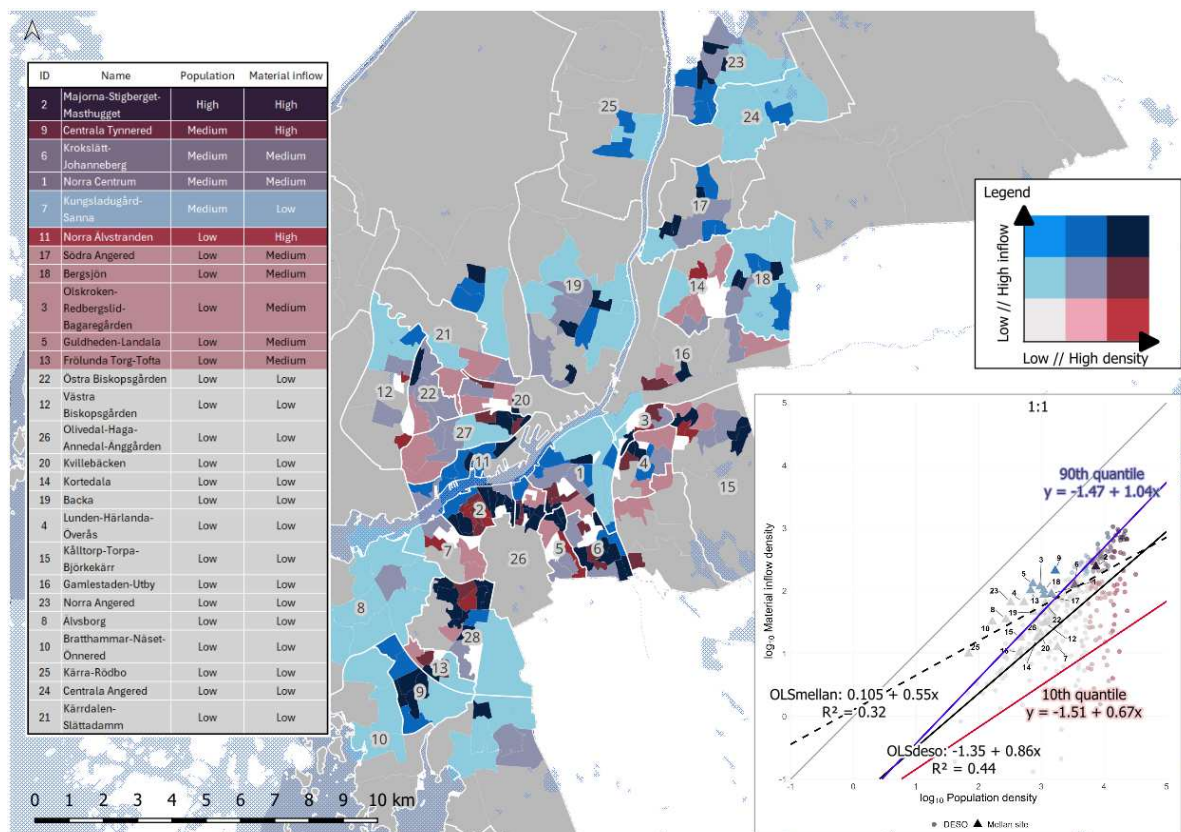


Figure 5. Spatial relationship between 2015 population density and cumulative residential material-inflow density between 1960 and 2015. Bivariate distribution across Demographic Statistical Areas, with colours representing combinations of population density and cumulative material-inflow density; log-log relationship between population density and cumulative material-inflow density, showing the ordinary least-squares estimate and conditional quantile regression estimates for the 10th and 90th quantiles.

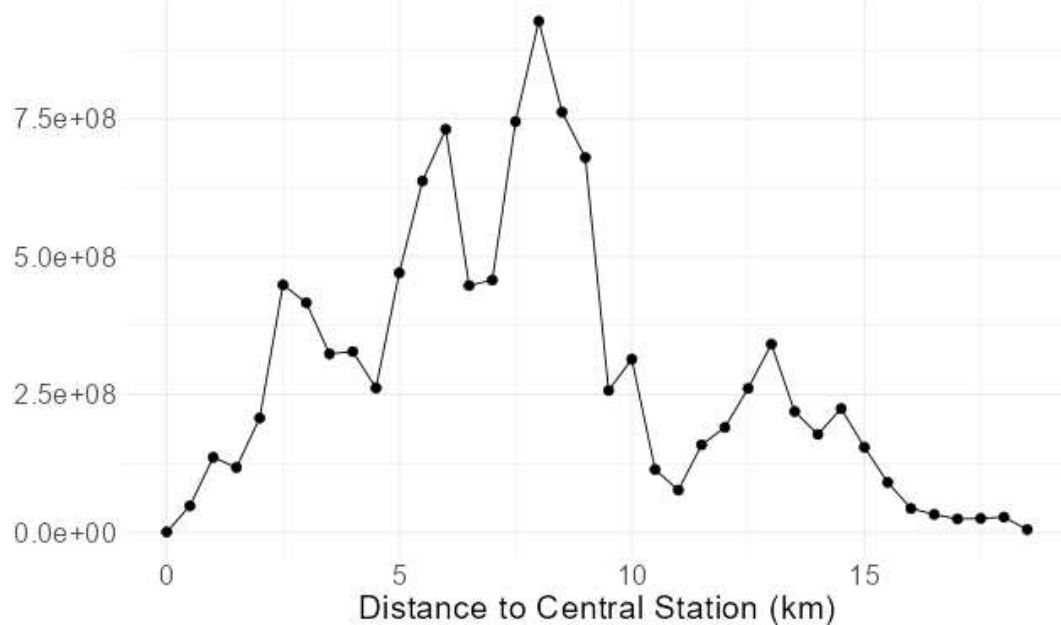
3.4. Spatial distribution of residential material inflows

Residential material inflows were concentrated primarily between 5 and 10 km from Gothenburg Central Station (Figure 6a). The largest inflow occurred at approximately 8 km, with additional concentrations around 6 and 13 km. Inflows declined markedly beyond approximately 15 km.

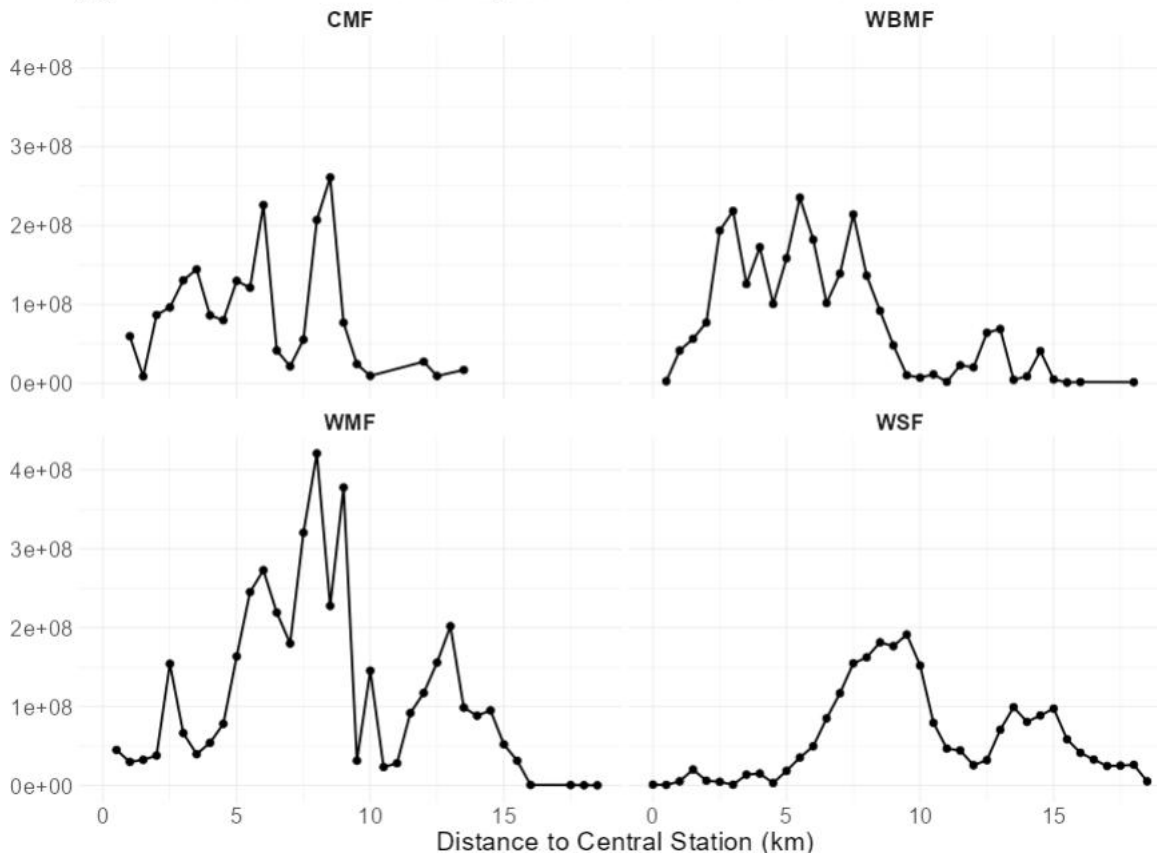
The distance distributions differed among residential structural typologies (Figure 6b). CMF inflows were concentrated between approximately 2 and 9 km, with peaks around 6 and 8 km. WBMF inflows extended across a broader range but were concentrated primarily between 5 and 10 km. WMF exhibited several peaks between approximately 5 and 9 km, together with a smaller concentration between 12 and 15 km. WSF inflows were concentrated farther from the centre, particularly between approximately 7 and 10 km, with a secondary concentration between 13 and 15 km.

The distribution also varied among construction decades (Figure 6c). Material inflows during the 1960s were concentrated primarily between approximately 5 and 8 km from the Central Station. The 1970s exhibited the largest concentration, particularly between approximately 6 and 8 km. Inflows during the 1980s and 1990s were smaller and more dispersed, while construction during the 2000s and 2010s produced smaller concentrations at several distances.

(a) New Construction GFA by Distance to Central Station



(b) New Construction Materials by Distance to Central Station



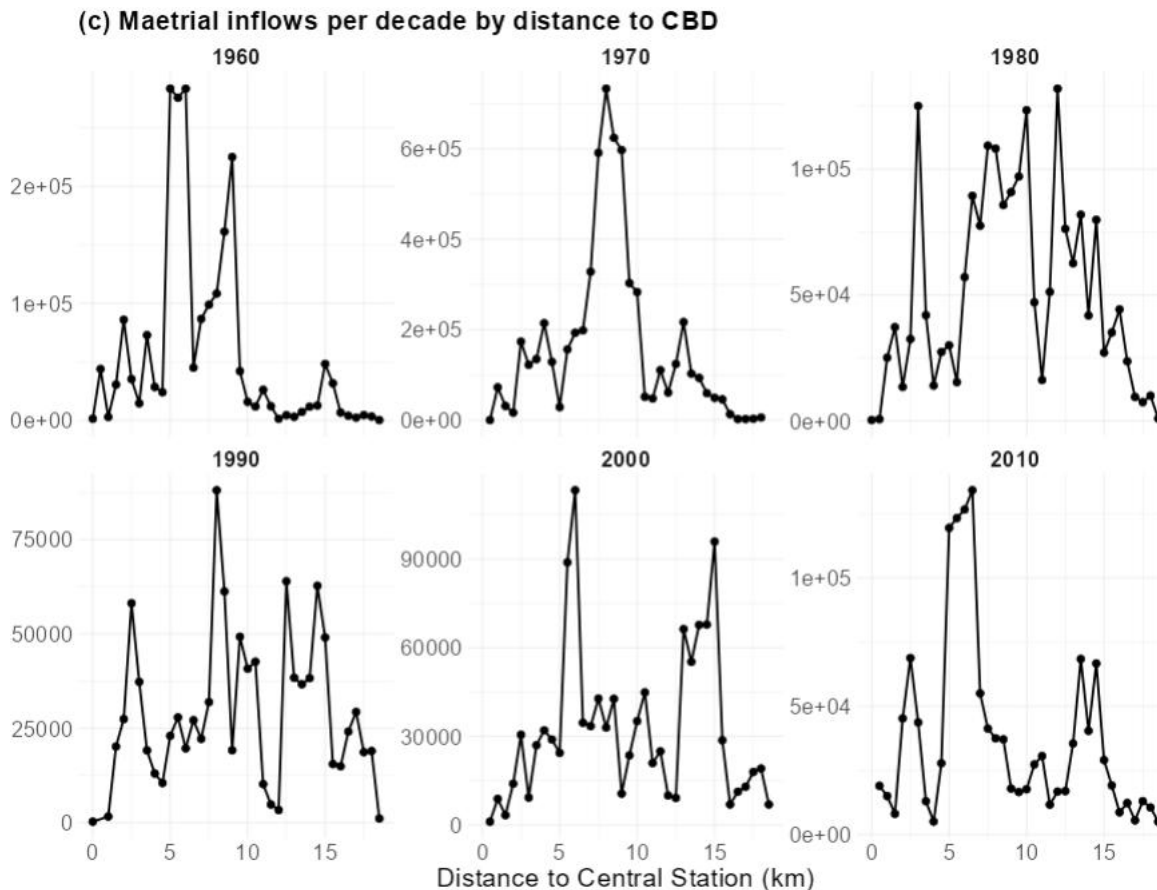


Figure 6. Distribution of residential material inflows from new construction by distance from Gothenburg Central Station. (a) Total residential material inflow within each distance band; (b) material inflows by residential structural typology; and (c) material inflows by construction decade.

3.5. Material composition and spatial distribution of residential material flows

Concrete accounted for the largest share of residential material inflows and outflows, followed by sand and aggregates and steel and cast iron (Figure 7). The remaining material categories contributed smaller shares, with relative contributions varying among construction and demolition periods.

Material outflows were concentrated in the earlier periods (Figure 7a). The largest outflow occurred in 1970–1975, followed by 1965–1970 and 1960–1965. Concrete dominated the outflows in each period. Limited or no demolition-related outflows were identified after 1990.

Material inflows were substantially larger than outflows and were highest in 1965–1970, followed by 1970–1975 and 1960–1965 (Figure 7b). Inflows declined during the 1980s and 1990s before increasing during the 2000s. Concrete remained the largest material component throughout the study period.

Cumulative material inflows increased most rapidly during the 1960s and 1970s and continued to rise more gradually thereafter (Figure 7c). By 2015, cumulative residential material inflows from new construction reached approximately 10.89 Mt. Concrete made the largest contribution, followed by sand and aggregates and steel and cast iron.

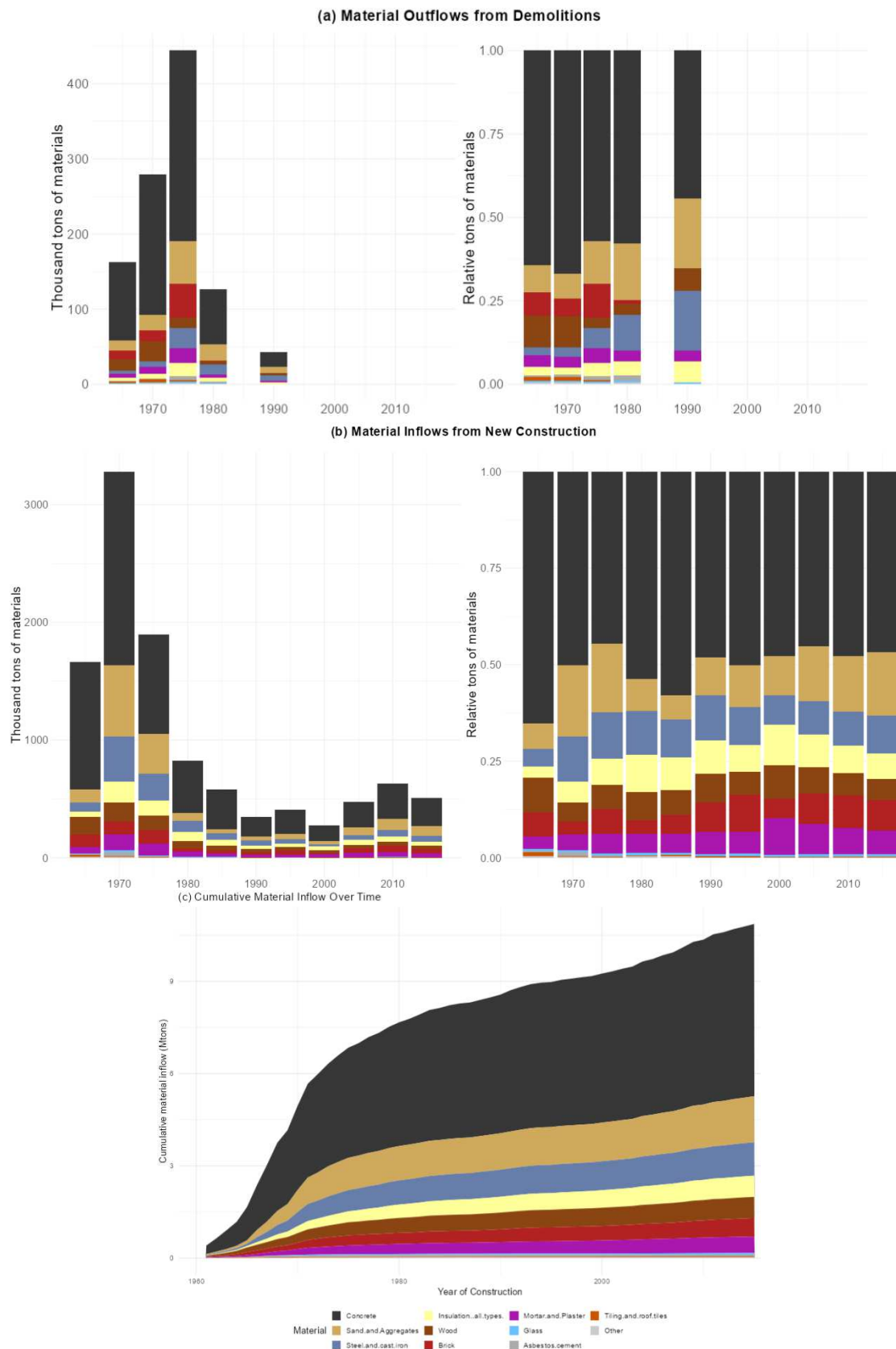


Figure 7. Composition of residential material flows associated with construction and demolition between 1960 and 2015. (a) Absolute and relative composition of material outflows from demolished residential buildings by five-year period; (b) absolute and relative composition of material inflows from newly constructed residential buildings by five-year period; and (c) cumulative material inflows from newly constructed residential buildings by material category.

The spatial distribution of residential material inflows changed over time (Figure 8). The largest and most concentrated inflows occurred during the 1960s and 1970s, particularly in southern and southwestern Gothenburg, with additional concentrations north and east of the central urban area.

After 1975, inflows decreased and became more dispersed. During the 1980s and 1990s, smaller concentrations were distributed across southern Gothenburg and parts of Hisingen. The periods from 1995 to 2015 exhibited lower overall intensities and more isolated concentrations than the earlier construction periods. Spatial distributions by individual material category are provided in Supplementary Material 3.

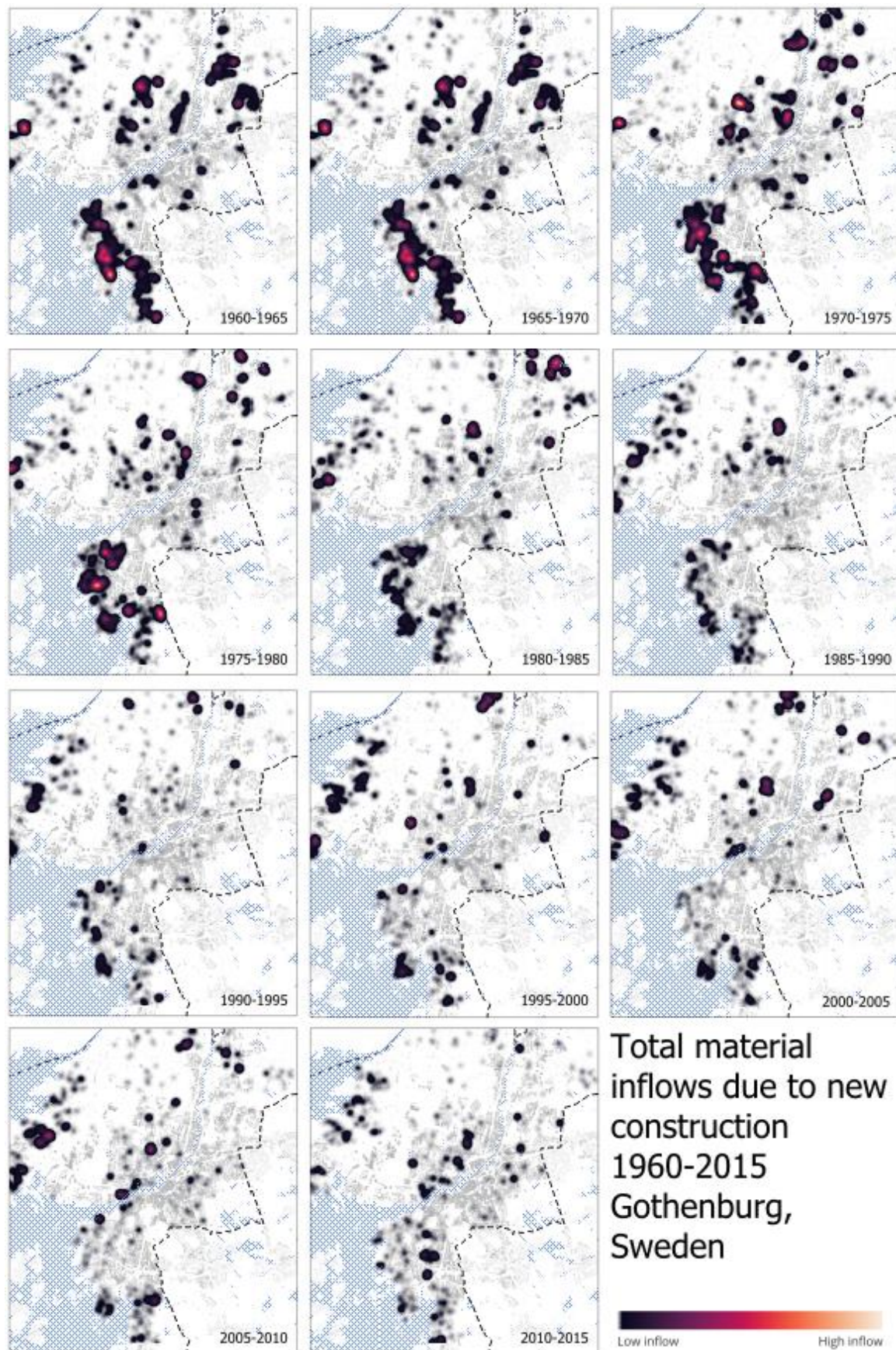


Figure 8. Spatial distribution of residential material inflows associated with new construction in Gothenburg between 1960 and 2015. Each panel shows the spatial concentration of total residential material inflows during a five-year construction period, with lighter colours indicating higher concentrations.

4. Discussion

4.1. Urban growth and residential material accumulation

Gothenburg underwent substantial physical expansion between 1960 and 2015. While population increased by approximately 29%, residential footprint and GFA both increased by approximately 102%. Residential floor area therefore grew considerably faster than population, indicating that demographic change alone does not adequately represent the physical expansion of the city. Similar divergences between population and material-stock growth have been observed across Swedish municipalities and in Germany (Gontia et al., 2020; Schug et al., 2023).

Construction was concentrated in the late 1960s and early 1970s, corresponding to Gothenburg's period of large-scale residential development and industrialised housing construction. However, building counts, added GFA, and material inflows followed different temporal patterns. The largest number of residential additions occurred in 1970–1975, whereas the largest additions of GFA and materials occurred in 1965–1970. Building counts alone therefore provide only a partial measure of the physical magnitude of urban growth.

Official dwelling statistics provide an independent consistency check of the reconstructed trajectory. Although completed dwellings and individual buildings are not directly comparable, the official series similarly indicate lower residential construction during the 1980s and 1990s and renewed growth after 2000. The agreement in the broad temporal pattern supports the plausibility of the reconstruction but does not validate its absolute numbers of buildings, floor area, or materials. Statistics Sweden's construction series measures completed dwellings in newly constructed buildings and distinguishes between one- or two-dwelling and multidwelling buildings, making its observational unit different from the building polygons used here (Statistics Sweden (SCB), 2026a, 2026b).

Approximately 10.89 Mt of residential materials entered the building stock through new construction, with almost two-thirds of these inflows occurring between 1960 and 1975. Identified demolition outflows were considerably smaller and concentrated mainly in the earlier periods. This imbalance indicates that the residential stock remained in a phase of net accumulation throughout most of the study period.

These results also demonstrate the importance of distinguishing stocks from flows. Material stocks represent quantities embedded in buildings at a given time, whereas construction inflows and demolition outflows describe the processes through which those stocks change. Figures 4c and 7c show cumulative construction inflows by structural typology and material category, respectively, rather than the total in-use stock. Comparing only initial and final stocks would conceal the timing, composition, and spatial distribution of the underlying construction and demolition processes.

4.2. Spatial patterns of material accumulation

Residential material inflows were unevenly distributed across Gothenburg. The largest concentrations occurred mainly between 5 and 10 km from Gothenburg Central Station, particularly during the 1960s and 1970s. Later inflows were smaller and more dispersed. Their spatial distributions also differed among structural typologies, with WSF inflows concentrated farther from the centre than the multifamily typologies. The present geography of residential materials therefore reflects successive periods of development involving different building types and locations.

At the DeSO level, 2015 population density was positively associated with cumulative residential material-inflow density for 1960–2015. The estimated elasticity of 0.86 indicates that a 10% difference in population density was associated with approximately 8.6% higher cumulative material-inflow density. However, population density explained approximately 44% of the spatial variation, and the estimated relationship varied across the conditional distribution. Contemporary population concentration therefore captures only part of the historical geography of residential construction.

The relationship remained positive after aggregation to the 23 Mellan sites, but the estimated elasticity decreased to 0.55 and the explained variance to approximately 32%. At this scale, a 10% difference in 2015 population density was associated with approximately 5.5% higher cumulative material-inflow density. The persistence of a positive association across both spatial divisions supports the general relationship, but the change in magnitude shows that it is sensitive to spatial aggregation.

The weaker Mellan-level association likely reflects the greater internal heterogeneity of the larger areas. Aggregating smaller DeSO units combines locations with different densities, building types, development histories, and land uses, smoothing local concentrations of population and material inflows. This sensitivity is consistent with the modifiable areal unit problem, whereby regression results can vary with the scale and configuration of the spatial units used for aggregation. Recent spatial-methodological research emphasises that changes in spatial resolution and zonation can affect both descriptive patterns and model estimates (Lee et al., 2025; Nieves et al., 2024).

The two models should therefore be interpreted as complementary rather than competing estimates. The DeSO results capture finer-grained spatial correspondence, whereas the Mellan results describe broader urban areas and are less influenced by highly localised variation. The reduction in the coefficient and explanatory power at the Mellan scale indicates that relationships observed at one spatial resolution should not automatically be generalised to another.

The mapped results reinforce this interpretation. Several central and established areas combined high contemporary population density with high cumulative material-inflow density, while parts of Angered, Bergsjön, and Älvsborg contained substantial historical inflows relative to their 2015 population density. Such differences may reflect variations in building form, development intensity, structural typology, land availability, and the timing and persistence of residential development.

Urban morphology may provide an additional basis for explaining these patterns. Plots define the units through which land is owned, regulated, subdivided, and redeveloped and can therefore shape opportunities for intensification, replacement, and demolition. The present analysis does

not isolate these mechanisms, but the building-level reconstruction provides a basis for examining how plots, accessibility, and surrounding urban form relate to building turnover.

4.3. Methodological contribution

The main methodological contribution is the integration of historical building turnover, machine-learning-based attribute enrichment, spatial context, and material accounting within a common building-level framework. By comparing consecutive historical layers, the approach identifies observed additions and removals rather than relying exclusively on assumed building lifetimes. It therefore complements spatially explicit material-stock studies based on GIS and building inventories (Heeren & Hellweg, 2019; Kleemann et al., 2017; Tanikawa & Hashimoto, 2009).

Machine learning addressed missing information on historical building function and residential structural typology. Contemporary labelled observations were combined with morphological and spatial variables to enrich the historical building layers, extending previous morphology-based structural classification in Gothenburg (Bian et al., 2026). Historical buildings were characterised using the street network corresponding to each period rather than the contemporary network, preserving temporal consistency between buildings and their spatial context.

The building-level representation retains the connection between building characteristics, location, temporal status, and material quantities. Stocks and flows can therefore be aggregated by period, spatial unit, structural typology, and material category without losing their building-level origin. This provides a basis for tracing not only how much material accumulated but also when and where the associated construction and demolition occurred.

4.4. Limitations and future research

The historical reconstruction draws on datasets of varying completeness, creating uncertainty in building dates, attributes, and matching across periods. The limited demolition detected in later periods may partly reflect these constraints and should not be interpreted as an absence of demolition.

Building function and residential structural typology were inferred using XGBoost models trained on contemporary observations. Although predictive performance was high, XGBoost does not provide conventional standard errors for individual predictions, and its class probabilities cannot be interpreted as calibrated measures of uncertainty without additional assessment. Like other complex ensemble models, it also offers limited interpretability compared with conventional statistical models (Rudin, 2019). Classification uncertainty was not propagated into the material estimates, although incorrect structural assignments can affect both estimated mass and material composition (Bian et al., 2026). Material-intensity coefficients introduce further uncertainty because buildings within the same typology may differ in age, construction technology, and material composition. Future studies could combine calibrated class probabilities with probabilistic material-intensity coefficients.

The system boundary was restricted to residential buildings and whole-building construction and demolition. It excludes non-residential buildings, roads, railways, pipes, and other infrastructure, as well as renovation, extension, changes of use, and partial demolition. These omissions are substantial: an earlier assessment of Gothenburg attributed approximately 72% of built-environment material stocks to buildings, 27% to roads, and 1% to pipes (Gontia et al., 2019). The present results therefore represent residential building metabolism rather than the city's complete material metabolism. Extending the framework to non-residential buildings,

infrastructure, and partial building transformations would provide a more comprehensive account.

Finally, the population analysis compares 2015 population density with material inflows accumulated over 1960–2015 and is sensitive to the spatial units used. Historical demographic and land-use data, together with alternative spatial divisions, would enable a more direct analysis of demographic change, urban form, and material accumulation over time.

5. Conclusion

This study developed a building-level framework for reconstructing long-term building-stock dynamics by integrating historical GIS, building and network characteristics, machine-learning-based attribute enrichment, and material-flow accounting. Applied to Gothenburg between 1960 and 2015, the framework identified building construction and demolition at five-year intervals and quantified the residential material flows associated with these changes.

The reconstruction shows that demographic and physical development followed different trajectories. Gothenburg's population increased by approximately 29%, while residential footprint and GFA both increased by approximately 102%. Construction was concentrated in the late 1960s and early 1970s, but the periods with the largest numbers of additions did not always coincide with those producing the largest additions of floor area or material.

Approximately 10.89 Mt of residential materials entered the building stock through new construction during the study period. These cumulative construction inflows, shown by structural typology and material category, were concentrated in the first 15 years of the reconstruction. Demolition-related outflows were considerably smaller and were concentrated primarily in the earlier periods.

Residential material inflows were distributed unevenly across Gothenburg. The largest concentrations occurred mainly between 5 and 10 km from Gothenburg Central Station, and their distance distributions varied among structural typologies and construction decades. Population density in 2015 was positively associated with cumulative residential material-inflow density, but substantial spatial variation remained. Contemporary population distribution therefore captures only part of the historical geography of residential construction and material accumulation.

The principal contribution is a common building-level representation of historical turnover, inferred building attributes, spatial context, and residential material flows. By retaining the location and temporal status of individual buildings, the framework moves beyond static material inventories and provides an empirical representation of how material stocks are formed and modified through construction, persistence, and demolition.

The framework can support future analyses of building transformation, demolition, secondary-material availability, and urban circularity. Further development should extend the material accounting to non-residential buildings, incorporate renovation and partial transformation, and propagate uncertainty from building classification and material-intensity coefficients into the final estimates.

Appendix

Table 1. Summary table of counts, footprint, GFA and total material inflow per period

Metric	1960–1965	1965–1970	1970–1975	1975–1980	1980–1985	1985–1990	1990–1995	1995–2000	2000–2005	2005–2010	2010–2015	Total
OUTFLOW - DEMOLITIONS												
Count	90	157	176	49	0	44	0	0	0	0	0	516
Footprint (km ²)	0.08	0.11	0.12	0.05	0.00	0.02	0.00	0.00	0.01	0.00	0.00	0.39
GFA (km ²)	0.20	0.34	0.40	0.12	0.00	0.05	0.00	0.00	0.00	0.00	0.00	1.12
Mass (Mt)	0.16	0.28	0.44	0.13	0.00	0.04	0.00	0.00	0.00	0.00	0.00	1.05
INFLOW - NEW CONSTRUCTIONS												
Count	3,656	5,225	5,853	4,499	2,936	1,876	1,513	2,134	2,381	2,074	1,344	33,491
Footprint (km ²)	0.82	1.45	1.06	0.71	0.44	0.33	0.28	0.30	0.35	0.34	0.28	6.35
GFA (km ²)	2.16	3.57	2.34	1.18	0.77	0.54	0.53	0.51	0.69	0.80	0.59	13.69
Mass (Mt)	1.67	3.28	1.90	0.82	0.58	0.35	0.41	0.28	0.47	0.63	0.51	10.89
NET CHANGE												
Count	3,566	5,068	5,677	4,450	2,936	1,832	1,513	2,134	2,381	2,074	1,344	32,975
Footprint (km ²)	0.7	1.3	0.9	0.7	0.4	0.3	0.3	0.3	0.3	0.3	0.3	5.96
GFA (km ²)	2.0	3.2	1.9	1.1	0.8	0.5	0.5	0.5	0.7	0.8	0.6	12.57
Mass (Mt)	1.5	3.0	1.5	0.7	0.6	0.3	0.4	0.3	0.5	0.6	0.5	9.83

Table 2. Summary description of stock and flows at the start and ending of period

Gothenburg	1960	Net addition	2015	Increase
Population	443,843	128,956	572,799	29%
Population density (resi/km2)	992.9		1281.4	
Total footprint	10.8	13.1	23.9	121%
Residential stock per capita (t/pc)*	56.3	75.6	60.6	8%
Residential footprint	5.8	5.9	11.7	102%
Residential GFA (km2)	17.7	18.0	35.7	102%
Accumulated stock (Mt)**	24.971	9.7	34.72	39%

*Net residential material accumulation per additional inhabitant

Net material accumulation

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