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From Expansion to Renewal: Material Metabolism and Secondary Resource Potential of Urban Buildings in China Western Central Cities

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Abstract

Amid China's transition from rapid urbanization to high-quality development, quantifying urban building metabolism is crucial for building resilient resource management systems. However, current research predominantly focuses on eastern cities, largely overlooking non-residential buildings. Here, we apply dynamic material flow analysis (dMFA) to quantify the material stocks of residential and non-residential buildings in two major economic hubs in western China, Xi'an and Chengdu. The stock patterns from 1950 to 2050 and the underlying drivers are further clarified. Model projections suggest that material stocks in both cities will peak around 2040, reaching 2.2 billion tons in Chengdu and 1.08 billion tons in Xi'an, under the intensive scenario. Chengdu reaches stock saturation 2 to 3 years earlier than Xi'an, and the total stocks are approximately twice those of Xi'an. Reinforced concrete and steel structures dominate future building development and increase the accumulation of cement and steel. Sand and gravel still account for the majority of building materials. Demand for new construction materials shows a pronounced double-peak pattern, occurring in 2016 and 2026. Construction waste is projected to rise sharply by mid-century; scenario analysis indicates that an 80% material recovery rate has the potential to largely offset new material demand. Sensitivity analysis identifies building lifetime extension and construction technology improvement as the strategies with the greatest potential for mitigating future waste generation. This study expands the scope of urban building material metabolism research and provides a scientific basis for low-carbon urban planning and construction waste management in China.

Keywords: material metabolism; dynamic material flow analysis; western central city; non-residential buildings; secondary resource circulation

Academic Editor: Francesco Nocera

Received: 2 April 2026
Revised: 2 June 2026
Accepted: 15 June 2026
Published: 23 June 2026

1. Introduction

1.1. Background

Building materials constitute the physical foundation of cities, and approximately half of all raw materials extracted from the natural environment are converted into building materials and products [1,2]. Owing to their relatively long service life, materials such as sand, gravel, cement, steel, bricks, and wood gradually accumulate as substantial in-use stocks [3]. The inevitable aging of these stocks renders them a massive and persistent

https://doi.org/10.3390/buildings16132481

source of solid waste [4], positioning the construction industry as a major sector for both natural resource consumption and solid waste generation and a potential reservoir of secondary resources, i.e., an "urban mine". In China, building stock nearly doubled between 2000 and 2020 [5], while early high-speed urban renewal has shortened building lifespans [6], accelerated material metabolism, intensified waste management pressure, and increased greenhouse gas emissions. As China's urbanization enters the "second half," the urban development paradigm is shifting from large-scale incremental expansion to stock upgrading and renewal. Accurately quantifying building stock, material flow metabolism, and the associated driving factors is, therefore, of great significance for achieving urban sustainable development goals (e.g., the United Nations SDG 11 [7]) and advancing the circular economy through urban mining [8,9].

This transition is particularly consequential for western central cities, such as Xi'an and Chengdu. As anchor nodes of the national Western Development Strategy and the Belt and Road Initiative, these cities entered the rapid stock accumulation phase later than eastern megacities and are now simultaneously confronted with peaking new construction demand and an imminent surge in demolition waste. Unlike eastern coastal cities whose building metabolism has been extensively documented, the long-term stock trajectory, structural composition, and secondary resource potential of western central cities remain poorly quantified—a gap with direct implications for low-carbon urban planning and construction and demolition waste (CDW) management policy in inland China.

1.2. Literature Review

Material flow analysis (MFA) is the predominant method for studying material stock [10], and it can be broadly classified into static approaches (top-down and bottom-up accounting) [11,12] and dynamic approaches (flow-driven or stock-driven). The static top-down method quantifies materials based on input–output relationships within the socioeconomic system and is commonly applied at global [13–15] and national scales [16–19]. The bottom-up accounting method disaggregates MS (material stock) into product categories, estimates each category by multiplying material intensity by product quantity, and sums the results to obtain total stock. This method mainly focuses on specific substances or specific substance categories and rarely focuses on the overall urban MS [9,20]. However, static MFA fails to capture the dynamic interplay between flow and stock over extended time horizons, neglects the lifecycle characteristics of stock, and is limited in forecasting future stock and waste flows [21]. In contrast, dynamic material flow analysis (dMFA) models the full lifecycle of materials across long time series, employing deterministic or stochastic functions to simulate waste generation from aging stock products [22]. Since Müller's archetypal stock-driven dMFA framework for the Dutch dwelling stock [12], the approach has been extended through segmented dwelling stock models in Europe [23] and probabilistic formulations that explicitly propagate parameter uncertainty [24]. As Müller proposed, service demand growth is fundamentally driven by lifestyle changes, with per capita floor area serving as a proxy for living standards [12]; accordingly, building stock dynamics can be primarily attributed to per capita floor area and population. Given these advantages in long-term trend prediction, this study adopts stock-driven (i.e., demand-driven) dynamic material flow analysis.

Within China, dMFA has been widely applied to estimate building stock [25,26] and associated material inflows and waste flows [12,27–29]. Hu et al. [26,30] pioneered the analysis of Chinese urban and rural housing stocks and used dMFA to forecast strategic CDW flows in Beijing; Cao et al. [6,24] subsequently refined the framework through lifetime calibration and probabilistic uncertainty analysis; and Gao et al. [21] integrated rural–urban land transition into a dMFA of residential buildings in Shanghai, showing that ignoring this transition can underestimate urban demolition waste by up to 57%. At the national scale, Song et al. [31] and the UPBIMS dataset compiled by Li et al. [32] provide the most spatially complete bottom-up benchmarks to date.

However, the existing literature reveals significant gaps in dMFA application, particularly in China, where the construction boom occurred much later than in the United States and the European Union [33]. First, most studies focus on developed eastern cities, such as Beijing and Shanghai, paying insufficient attention to western central cities, such as Xi'an and Chengdu, that serve core functions under the national Western Development Strategy [9,10,21]. Second, existing models often adopt a coarse classification of building structures, neglecting the heterogeneity among steel, brick–wood, and other structural types and lacking a comprehensive analysis across both building types and structures. For instance, Lu et al. [34] projected construction and demolition waste (CDW) generation from urban and rural residential buildings in a Chinese urban agglomeration comprising Fuzhou, Xiamen, and Quanzhou through 2100 but did not differentiate building structures. Third, current research is largely confined to residential buildings, generally overlooking commercial, office, and other non-residential buildings that contribute substantially to construction and demolition waste [12,30,35–37]. These limitations collectively lead to an underestimation of the overall scale of urban material metabolism. Beyond quantifying metabolism, a parallel stream of research has examined how CDW can be managed and recycled. At the operational level, enhancement strategies for CDW recycling, such as organizing temporary on-site bins, identifying activities that produce recyclable materials, and strengthening company recycling policies, have been systematically identified and prioritized [38], and their effectiveness evaluated through multi-criteria approaches [39]. Upstream, design, and pre-contract-stage interventions, such as Building Information Modeling (BIM), have been shown to curb waste at its source by reducing design complexity, contract document errors, and frequent design changes [40]. However, these management-oriented studies are predominantly project- or firm-level and survey-based, treating the scale, timing, and material composition of waste flows as given rather than quantifying them; their effective targeting therefore presupposes the long-term, spatially and structurally explicit waste accounting that remains scarce for western Chinese cities and the non-residential sector.

To address these research gaps, this study constructs a dynamic material flow accounting model and a Logarithmic Mean Divisia Index (LMDI) driving factor decomposition model for urban residential and non-residential buildings, covering four structural subtypes and nine material categories. Through historical data reconstruction (1950–2024) and multi-scenario projection (2025–2050), this study systematically reveals the century-long evolution patterns and inter-city disparities in building material stocks and flows in Xi'an and Chengdu, two representative economic hub megacities in western China. It further quantitatively analyzes the driving mechanisms of building material accumulation in the two cities and focuses on evaluating the resource utilization potential of construction waste. This study expands the quantitative research perspective on building material metabolism in western Chinese cities and non-residential buildings. The research conclusions can provide a scientific basis and data support for the formulation of low-carbon urban planning, long-term building resource management, and construction waste reduction policies in western China.

2. Materials and Methods

2.1. Research Framework

As shown in Figure 1, this study integrated stock-driven dynamic material flow analysis (dMFA) and LMDI decomposition to quantify the century-long building material metabolism in Xi'an and Chengdu, two western economic central cities in China, and to reveal their long-term evolution patterns. Specifically, historical data were collected from national and provincial statistical yearbooks, successive census data, and the existing literature (M1), and all parameters were projected into the future. Three macro-development scenarios, intensive development, quality improvement, and moderate expansion, were constructed by combining different gradients of population, per capita floor area, and building lifespan (M3). A stock-driven dMFA model then simulated the building area and material inflow, stock, and outflow of residential and non-residential buildings across four structural types and nine materials from 1950 to 2050, and the resulting stock was rasterized to characterize spatial distribution patterns (M2). The LMDI method was further applied to decompose the driving factors of stock changes (M4), and the secondary resource recovery potential of construction waste was assessed under multiple recycling scenarios (M5). Finally, the output module synthesizes the results of stock evolution, material flow, waste projection, and resource potential, providing a scientific basis for low-carbon urban planning and construction waste management in western China (M6).

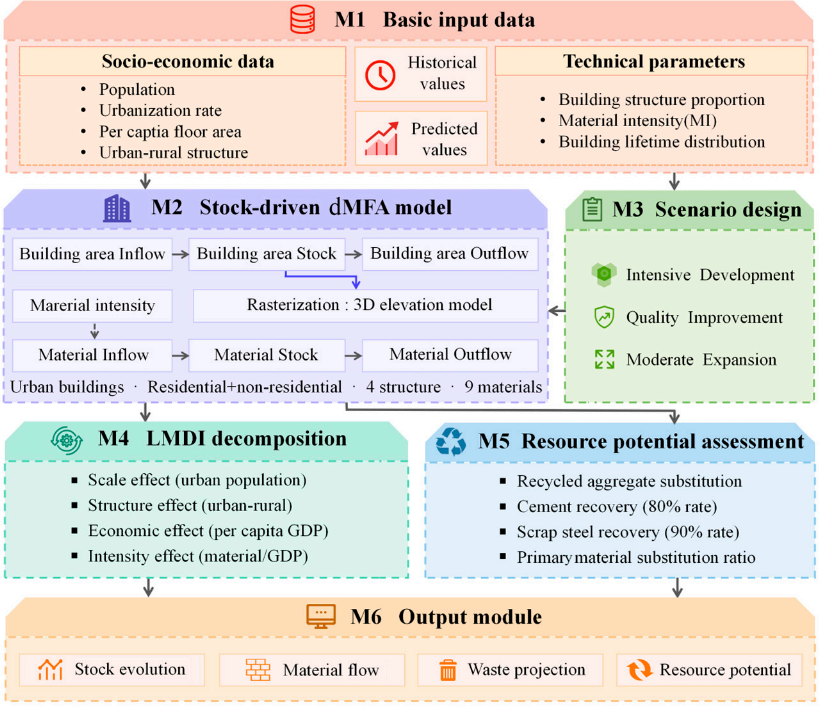

Figure 1. Workflow for material metabolism and secondary resource potential prediction of urban construction stock in western central cities.

2.1.1. Construction of the Dynamic Material Flow Model

Based on the historical and predicted data above, dynamic material flow models for urban buildings in Chengdu and Xi'an from 1950 to 2050 are established. The specific formulas of the models are shown in Equations (1)–(8), respectively.

$$S_t = A_t \times P_t \times U_t \tag{1}$$

$$N_{i,t} = N_t \times w_{i,t} \tag{2}$$

where S_t is the total urban construction area in year t, A_t is the urban per capita residential or per capita non-residential area in year t, P_t is the total population (permanent resident) in year t, U_t is the urbanization rate in year t, $N_{i,t}$ is the new construction area of residential and non-residential buildings in structure i in year t, and $w_{i,t}$ is the proportion of residential and non-residential buildings in structure i in new buildings, in which $N_1 = S_1$ (no prior building stock exists; all floor area in t_0 is treated as inflow).

$$\mathrm{OUT'}_{i,t} = \sum\nolimits_{t'=1}^{t} N_{i,t'} \times L_i\left(t, t'\right) \tag{3}$$

$$L_i\left(t, t'\right) = \frac{1}{\sigma_i\sqrt{2\pi}} \times e^{-\frac{\left(t-t'-\tau_{i,t'}\right)}{2\sigma_i{}^2}} \tag{4}$$

$$N_t = S_t - S_{t-1} + \sum\nolimits_{i=1}^{n} \mathrm{OUT'}_{i,t^{-1}} \tag{5}$$

where $\mathrm{OUT'}_{i,t}$ is the outflow area of residential and non-residential buildings with structure i in the t' year, $N_{i,t'}$ is the inflow area of buildings with structure i in the t' year, $L_i(t,t')$ is the life distribution function of buildings with structure i, indicating the possibility of demolition of buildings built in the t' year, $\tau_{i,t'}$ is the average life of residential and non-residential buildings with structure i in year t', σ_i is the standard deviation of the lifetime distribution, set to one-third of the mean lifetime $\tau_{i,t}$, N_t is the total inflow of all buildings in the city, $\sum_{i=1}^{n} \mathrm{OUT}'_{i,t-1}$ is the sum of the outflow of all structural residential and non-residential buildings in the city, and n is the number of residential and non-residential building structure types.

$$\mathrm{In}_{m,i,t} = N_{i,t} \times \mathrm{MI}_{m,i,t} \tag{6}$$

$$\mathrm{OUT}_{m,i,t} = \sum\nolimits_{t'=1}^{t} \mathrm{In}_{m,i,t'} \times L_i\left(t, t'\right) \tag{7}$$

$$S_{m,i,t} = S_{m,i,t-1} + \mathrm{In}_{m,i,t} - \mathrm{OUT}_{m,i,t} \tag{8}$$

where $\mathrm{I}n_{m,i,t}$ is the inflow of material m in residential and non-residential buildings of structure i in year t, $\mathrm{MI}_{m,i,t}$ is the unit floor area content of material m contained in residential and non-residential buildings of structure i in year t, $\mathrm{OUT}_{m,i,t}$ is the outflow of material m in residential and non-residential buildings of structure i in year t, and $S_{m,i,t}$ is the stock of material m in residential and non-residential buildings of structure i in year t.

2.1.2. Constructing the LMDI Decomposition Model of Urban MS

Based on urban material stock accounting, this study uses the LMDI decomposition method to identify the driving factors of stock changes. According to existing research, GDP, population, urbanization rate, and material intensity are the key factors affecting the stock accumulation. Therefore, the study decomposes the evolution of building material stock in Xi'an and Chengdu from 1950 to 2020 into four driving effects: scale effect (urban population, P1), structure effect (urban–rural structure, U), economic effect (per capita GDP, a), and intensity effect (material utilization intensity, t). The model is as follows:

$$\mathrm{MS} = P_1 \times \frac{P}{P_1} \times \frac{G}{P} \times \frac{\mathrm{MS}}{G} = P_1 \times U \times A \times T \tag{9}$$

where MS is the total urban material stock (MT), P is the permanent resident population, P_1 is the urban population, G is the gross urban product, U = P/P_1 is the urban and rural structure, and A = G/P is GDP per capita, T = MS/G is the intensity of material utilization; that is, the stock consumed per unit of GDP.

$$\Delta\mathrm{MS} = \Delta\mathrm{MS}_{P1} + \Delta\mathrm{MS}_U + \Delta\mathrm{MS}_A + \Delta\mathrm{MS}_T \tag{10}$$

$$\Delta\mathrm{MS}_{P1} = \frac{\mathrm{MS}_t - \mathrm{MS}_{t-1}}{\ln\mathrm{MS}_t - \ln\mathrm{MS}_{t-1}} \ln\left(\frac{P_1^t}{P_1^{t-1}}\right) \tag{11}$$

$$\Delta\mathrm{MS}_U = \frac{\mathrm{MS}_t - \mathrm{MS}_{t-1}}{\ln\mathrm{MS}_t - \ln\mathrm{MS}_{t-1}} \ln\left(\frac{U^t}{U^{t-1}}\right) \tag{12}$$

$$\Delta\mathrm{MS}_A = \frac{\mathrm{MS}_t - \mathrm{MS}_{t-1}}{\ln\mathrm{MS}_t - \ln\mathrm{MS}_{t-1}} \ln\left(\frac{A^t}{A^{t-1}}\right) \tag{13}$$

$$\Delta MS_T = \frac{MS_t - MS_{t-1}}{\ln MS_t - \ln MS_{t-1}} \ln\left(\frac{T^t}{T^{t-1}}\right) \tag{14}$$

Among them, ΔMS_{P1} reflects the impact of urban population size on urban MS; ΔMS_U represents the impact of urban–rural structure on urban MS; ΔMS_A represents the impact of economy on urban MS; and ΔMS_T reflects the impact of technological progress on urban MS changes.

2.2. Key Parameter Settings

Dynamic material flow analysis relies heavily on reliable long-term time series data. Historical statistics such as population size, urbanization rate, and per capita residential and non-residential floor area in urban areas primarily originate from national and provincial/municipal statistical yearbooks, the China Construction Industry Statistical Yearbook, successive census data, and the existing relevant literature. At the same time, various parameters are predicted.

The predicted urbanization rate is fitted using a logistic function, based on the future development plans of the two cities and the urbanization rate growth characteristics of developed countries. Three scenarios—high, medium, and low—are set for the forecasts of key parameters, including population, per capita building area, and building lifespan. The future population forecast data of the two cities are based on the research results of Zhang et al. [41], with the high, medium, and low scenarios corresponding to the different fertility and migration rate scenarios set in their study. Per capita building area is based on the research results of Liu, Q et al. [42], while future data follow a logistic function. Saturation values are calibrated against the development trajectories of European countries and Chinese policy targets. Given their inherent uncertainty, we conduct a sensitivity analysis in Section 4.1, treating population, per capita floor area, and building lifespan as the key perturbation parameters. The average lifespans for buildings are determined by analyzing the architectural characteristics, construction, and usage intensity across different eras, while also referencing relevant national standards and previous studies. The proportion changes in new building structures refer to the research results of An and Guo [33]. To highlight scale differences, the study assumes that the proportion of each structure evolves only with time and does not fluctuate with changes in scenario scale. The strength of building materials adopts research parameters from Yang et al. [43], Cao et al. [24], Guo et al. [44], Huang et al. [28], and Shi et al. [45]. Some parameters are estimated based on the “Construction Project Investment Estimation Manual,” taking into account differences in material strength among different building structures and buildings from different construction periods. The rationale for setting saturation values under different scenarios for each parameter and detailed underlying data sources is provided in the Supplementary Materials Note S1 and Tables S1 and S2. The fitting results of each parameter are shown in Supplementary Material Figure S1.

To scientifically predict the evolution trends of building material stock flows, this study constructs three future macro-development scenarios by scientifically combining different gradients of population, per capita building area, and building lifespan. The parameter combination matrix is shown in Table 1. Drawing upon the scenario design methodology of the Shared Socioeconomic Pathways (SSPs) [46], the scenario framework is constructed subject to the binding constraints imposed by the policy orientations for future construction models as stipulated in China’s key national policy documents, including The 14th Five-Year Plan for Building Energy Conservation and Green Building Development and Implementation Plan for Carbon Peaking in Urban and Rural Construction. It further integrates the stage-specific characteristics of China’s urbanization development to implement targeted localized adaptations. Specifically, building lifespans are assumed to remain at the medium lifespan level over the next 30 years based on the current development levels, construction intensities, technological renewal trends, and average building lifespans of the two cities.

Table 1. Development scenario parameter setting.

Scenario	Feature	Parameter Setting
Intensive Development Scenario	Compact city, efficient utilization of resources, and sustainable development	Population: medium Per capita residential area: low Per capita non-residential area: low Building life: medium
Quality Improvement Scenario	Quality-oriented, stock optimization, mature urban development path	Population: low Per capita residential area: medium Per capita non-residential area: medium Building life: medium
Moderate Expansion Scenario	Balanced development and resource constraints to meet the growth demand moderately	Population: high Per capita residential area: high Per capita non-residential area: high Building life: medium

3. Results

3.1. Dynamic Evolution of Building Construction Volume and Comparison Between the Two Cities

3.1.1. Growth Trajectory and Peak Difference

The simulation results indicate that between 1950 and 2050, both Xi'an and Chengdu exhibit typical S-shaped growth patterns in their building stock evolution. However, significant inter-city differences exist in terms of stock scale, flow fluctuations, and peak timing (Figure 2).

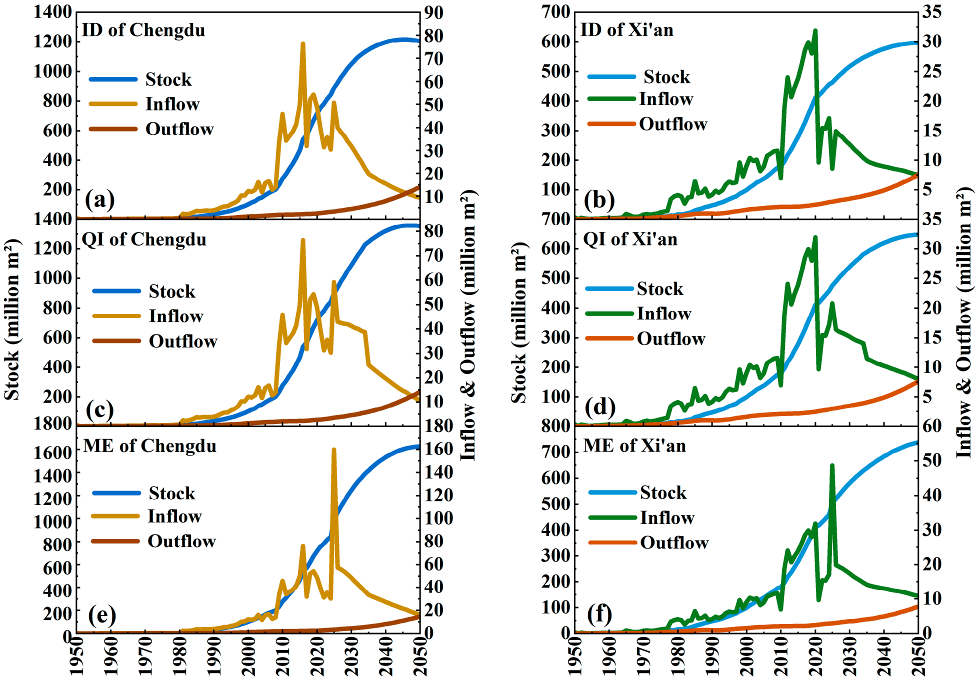

Figure 2. Urban building stock and flow in Chengdu and Xi'an from 1950 to 2050: (**a**,**b**) intensive development scenario (ID); (**c**,**d**) quality improvement scenario (QI); (**e**,**f**) moderate expansion scenario (ME).

In terms of growth trajectories, both cities' building stock evolution undergoes three distinct phases: gradual accumulation (1950–1990), exponential growth (1991–2025), and saturation transition (2026–2050). After 2000, Chengdu rapidly widened its gap with Xi'an due to higher material accumulation intensity. Under an intensive development scenario, Chengdu's total building stock is projected to peak around 2045 (approximately 1215 million m^2), roughly 2.05 times that of Xi'an during the same period (591 million m^2) (Figure 2a,b). This ratio is broadly consistent with the relative population size and built-up area extent of the two cities, suggesting that aggregate city scale may be a primary structural determinant of stock magnitude.

Both cities exhibit dual-peak patterns in new construction flows. Xi'an's inflow is more temporally concentrated, with sharper and steeper peaks, suggesting that its urban development investment has been compressed into shorter time windows. In contrast, Chengdu's inflow curve displays a flatter profile, with an additional secondary peak around 2010. This earlier surge is consistent with the large-scale post-earthquake reconstruction activities that followed the 2008 Wenchuan earthquake. Both cities reached their first primary peak between 2014 and 2016, coinciding with China's rapid real estate boom. Both cities are projected to experience a second inflow peak around 2026, a trajectory that is broadly consistent with the anticipated acceleration in urban renewal activities under the 14th Five-Year Plan; under intensive development scenarios, Chengdu's new construction inflection point (around 2026) is projected to occur 2–3 years earlier than Xi'an's.

The building demolition area exhibits significant temporal lag and exponential growth characteristics. Between 1950 and 2010, urban development primarily focused on incremental expansion. Most buildings remained in the physically and functionally sound phase of their lifecycle, with low abandonment probabilities according to their lifetime distribution functions. Additionally, the small base of early-stage urban stock had not yet entered a large-scale generational replacement cycle. The time lag between building investment and output kept demolition volumes extremely low. After 2020, as brick–concrete and brick–wood structures from earlier construction entered their end-of-life phase, demolition volumes began to surge. By the mid-21st century, outflow volumes in both cities will approach inflow volumes, marking the formal transition of urban material metabolism from an "incremental expansion-dominated" era to a "stock renewal-dominated" era.

Under the three development scenarios, the growth rate of the building stock in both cities exhibits a marginal diminishing trend. With Xi'an's volume at approximately 45–50% of Chengdu's, the moderate expansion scenario, driven by high population projections and relaxed per capita floor area indicators, projects that by 2050, the upper limits of building stock in Chengdu and Xi'an will exceed 1625 million m^2 and 738 million m^2, respectively (Figure 2e,f). At this point, cities will face immense resource consumption and environmental load pressures. Under the intensive development scenario, by controlling per capita building area and extending building lifespans, the peak building stock of both cities could decrease by approximately 20–25% compared to the expansion scenario. This suggests that controlling per capita building area and extending building lifespans may offer meaningful leverage over the long-term stock trajectory, a finding further quantified in the sensitivity analysis (Section 4.1).

To visually illustrate the spatial distribution patterns of the built stock in the two cities, we used the most recent GHSL building volume raster data to allocate the built stock to 500 m × 500 m grids and generated a gridded heatmap and a 3D elevation model (Figure 3). In terms of spatial patterns, both cities exhibit significant central clustering, but Chengdu has more numerous and dispersed secondary clusters, while Xi'an's clusters are more concentrated and exhibit stronger directionality.

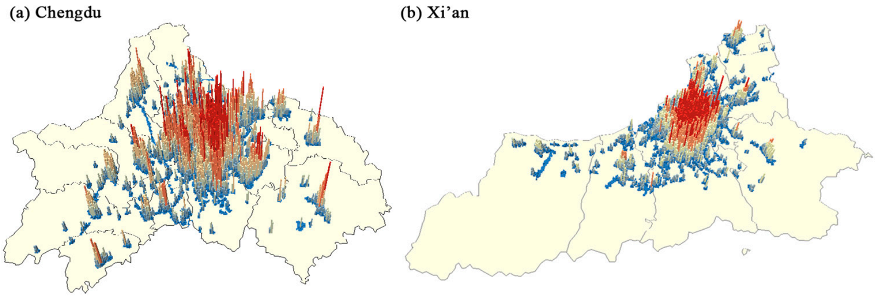

Figure 3. Distribution of the built-up area in Chengdu and Xi'an within 500 m × 500 m grids (Digital Elevation Model, 2023). The red areas indicate the highest density of built-up floor area.

3.1.2. Intergenerational Replacement of Building Structure and the Driving Effect of Non-Residential Buildings

Urban building structures evolved rapidly through four successive regimes: brick–wood (dominant in the 1950s), brick–concrete, reinforced concrete (entering explosive growth after the 1990s and peaking at over 93% of new construction in 2016), and steel frame structures (with prefabricated buildings becoming widespread after 2020) (Supplementary Material Figure S1e,f). Non-residential buildings exhibited earlier and more rapid structural modernization, adopting reinforced concrete structures at a higher rate and at an earlier point in time than residential buildings. This pattern, which is consistent with the functional requirements of large-span industrial facilities and high-rise public structures, is reflected in the structural proportion parameters used in this study (following Supplementary Material Figure S1e,f).

Low-strength buildings (brick–wood and brick–concrete structures) constructed between 1950 and 2000 have entered a concentrated phase of decommissioning, becoming the primary source of construction waste between 2010 and 2030 (Figure 4c,f). Although the proportion of steel structures in new buildings will increase significantly after 2025, reinforced concrete structures will still dominate the building stock in both cities, accounting for over 70% (Figure 4a,d). Given that reinforced concrete structures possess far greater material intensity per unit area than brick–concrete structures, the total accumulated steel and cement materials within cities will continue to expand even as future building area growth slows.

Residential and non-residential buildings exhibit distinct heterogeneity in their metabolic patterns. Residential structures consistently dominate the existing building stock. By 2050, residential buildings will account for approximately 57.1% of Chengdu's existing stock and a higher proportion of Xi'an's at around 64.4% (Figure 4g,j). The higher residential share in Xi'an's total stock (64.4% vs. 57.1% in Chengdu by 2050) indicates that residential construction has accounted for a larger proportion of urban material accumulation in Xi'an. In contrast, Chengdu's more balanced residential–non-residential distribution may reflect a relatively more diversified urban functional structure. Non-residential buildings exhibit faster metabolism. Following the second peak in inflow volume in 2026, Chengdu's non-residential inflow share approaches 51%, surpassing residential, highlighting its status as a regional commercial hub. In contrast, Xi'an maintains a slight advantage in residential inflow volume until 2050 (Figure 4h,k), indicating that over the next three decades, the construction of upgraded housing and the renewal of aging residential communities will remain the primary drivers of Xi'an's urban material metabolism.

Overall, Chengdu's material structure transition is relatively gradual. Influenced by post-2010 disaster reconstruction and subsequent commercial real estate development, its adoption of reinforced concrete and steel structures leads Xi'an in temporal sequence, with non-residential components contributing more significantly to overall metabolism. After 2015, the model captures a marked acceleration in the demolition of brick–concrete structures and a simultaneous increase in steel structure completions in Xi'an, a pattern broadly consistent with the large-scale urban village renewal programs undertaken during this period. The higher residential proportion indicates that Xi'an's future focus in construction waste management will persistently center on the metabolic byproducts of residential living spaces.

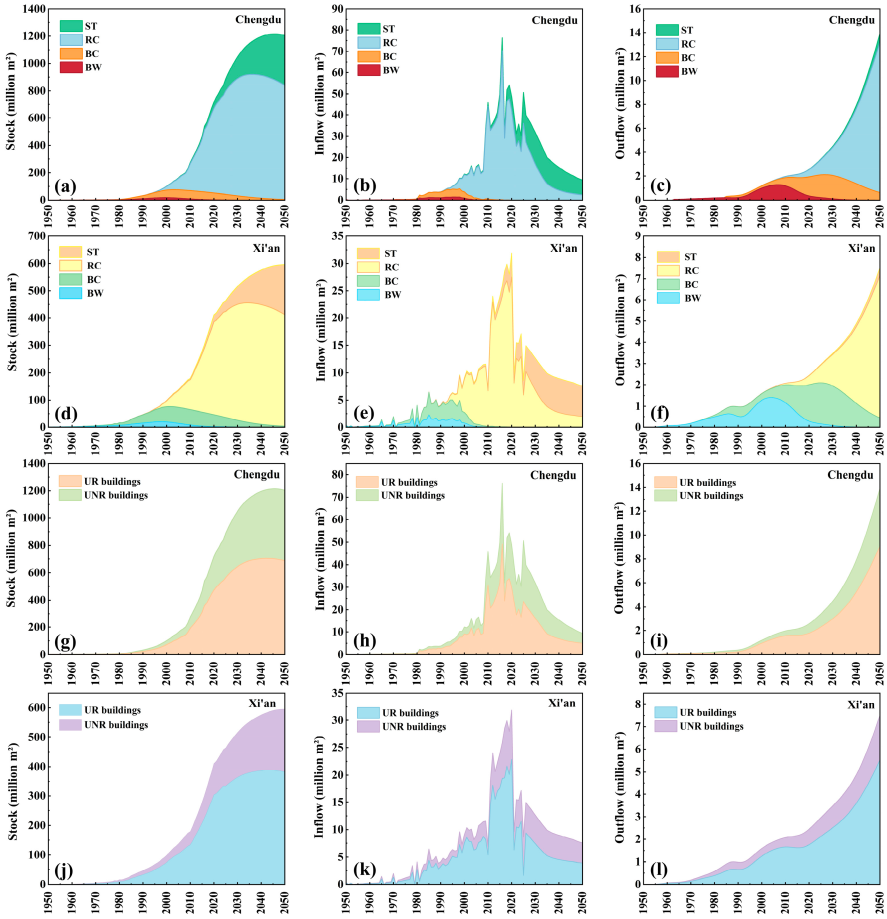

Figure 4. Contribution of urban building stock in Chengdu and Xi'an from 1950 to 2050 (intensive development scenario): (**a**–**f**) contribution of each structure (steel, reinforced concrete, brick–concrete structure, brick–wood); (**g**–**l**) contribution of residential and non-residential.

3.2. Material Metabolism Characteristics

3.2.1. Composition and Intensity of Material Stock and Flow

Between 1950 and 2050, the total stock of built environment in both cities surged in an S-shaped pattern, and it is projected to reach saturation by the mid-21st century. As a megacity and a major central city in western China, Chengdu demonstrated a stronger material accumulation capacity. The period from 1990 to 2030 represents its explosive accumulation phase, with growth rates significantly slowing after 2035 as it approaches a projected peak of approximately 2223 Mt under the intensive development scenario. Xi'an exhibits a similar growth pattern, but constrained by its physical scale, its volume is approximately 48.8% of Chengdu's. It is ultimately projected to converge at 1080 Mt (around 2040).

Accompanying the generational replacement of building structures (see Section 3.1.2), sand and gravel, core aggregates in concrete, will exhibit a sustained upward trend in proportion, becoming the most abundant "urban minerals." The share of gravel reserves in both cities will climb from approximately 16% in 1950 to around 35% by 2050 (Chengdu: 747 Mt, 35.1%; Xi'an: 370 Mt, 35.5%), making it the single largest material component. Sand's share remains stable at around 26% (Chengdu: 557 Mt, 26.2%; Xi'an: 270 Mt, 25.9%). By 2050, sand and gravel together account for over 61% of the total, forming the physical foundation of modern cities.

Cement and steel exhibit the fastest growth rates. Between 1950 and 2050, the proportion of cement stock steadily climbs from 4.6% to approximately 15% (Chengdu: 317 Mt, 14.9%; Xi'an: 151 Mt, 14.4%); steel's share surged from under 1% to approximately 6.5%. The two cities will accumulate over 200 Mt of steel resources (Chengdu: 136 Mt; Xi'an: 67 Mt), signaling immense future potential for scrap steel recycling. Bricks exhibit a classic inverted-U trajectory, declining from a dominance share in 1950 (Chengdu 52.9%, Xi'an 52.6%) to approximately 14% by 2050, with their absolute stock peaking around 2020. Wood, constrained by fire safety regulations and structural transformation, saw its share drastically reduced to negligible levels (<0.5%).

Material metabolism exhibits a pronounced "sensitive inflow, lagging outflow" response to technological change. On the inflow side, driven by the promotion of steel structures, new construction fully entered a high-energy-consumption phase between 2020 and 2030, with steel's share rapidly increasing. Concrete components (cement + sand + aggregate) accounted for as much as 76% (Figure 5c,d). On the outflow side, bricks constituted a significant proportion (over 43%) of demolition waste between 2010 and 2020, reflecting the large volume of early-stage brick–wood and brick–concrete residential structures completing their service lives during this period. This pattern is consistent with the known concentration of urban renewal activity in older residential neighborhoods during this decade. As demolition targets gradually shift toward early reinforced concrete structures, the proportion of concrete blocks (waste aggregates, waste mortar) in the outflow of both cities will rise significantly, climbing from 50% in 2010 to nearly 80% by 2050 (Chengdu: 78.5%, Xi'an: 77.9%) (Figure 5e,f).

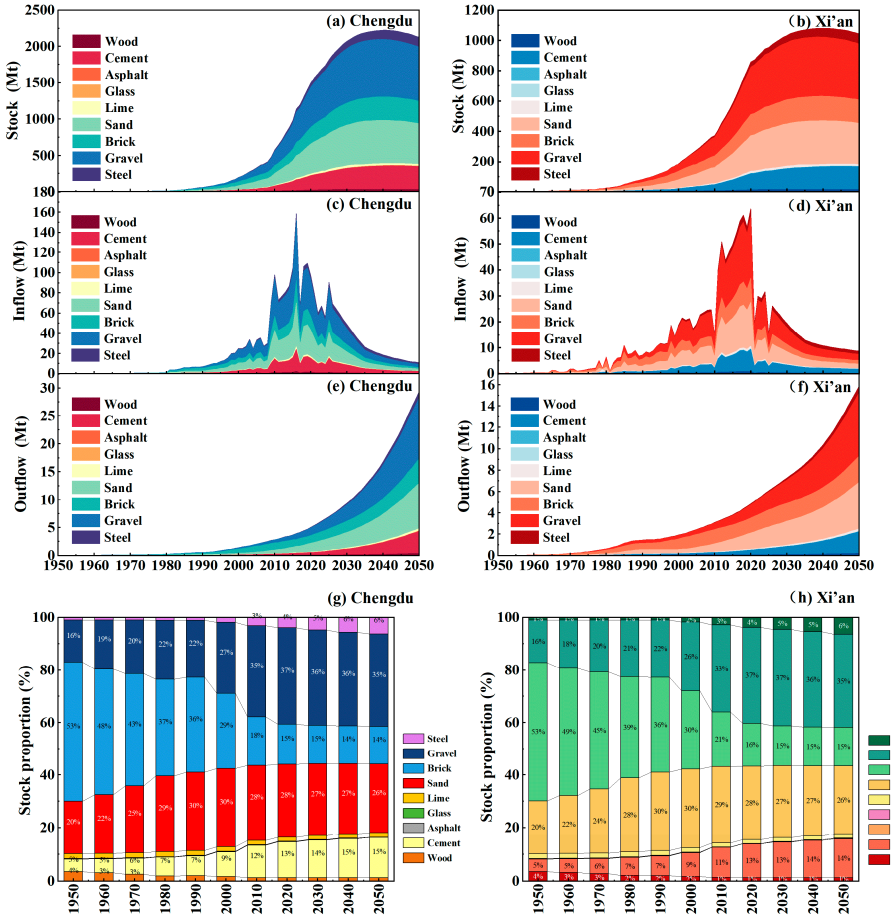

Figure 5. Composition of urban building stock in Chengdu and Xi'an from 1950 to 2050 (intensive development scenario): (**a**–**f**) evolution trend of nine kinds of materials; (**g**,**h**) proportion of each material stock component.

Comparing the two cities, their material stock compositions exhibit high homogeneity (Figure 5g,h), with differences in material proportions for all categories remaining within 0.5 percentage points by 2050. This reflects the common metabolic patterns of western central cities under unified national standards. However, in the temporal dimension, influenced by post-disaster reconstruction and earlier real estate boom cycles, Chengdu's material structure transformation (such as the point where crushed stone surpasses bricks in stock proportion) slightly leads Xi'an in the timeline.

3.2.2. Heterogeneity of Material Flow Between Residential and Non-Residential Buildings

Although residential buildings occupy a dominant position in the total construction area and total material stock, the pursuit of long-span, high-rise, and aesthetic functions of non-residential buildings (office, commercial, and public buildings) leads to significantly higher use intensity in high-carbon, high-energy-consumption, and high-recycling-value materials. Traditional mineral building materials such as brick, gravel, and sand are mainly concentrated in the residential sector. The brick stock of the residential sector in Chengdu is about 1.3 times that of the non-residential sector (Supplementary Material Figure S2a,c), while that of Xi'an is nearly 1.9 times (Supplementary Material Figure S2e,g). At the same time, as more concrete is consumed by non-residential buildings per unit area, the cement stock of non-residential buildings in the two cities will rise to about 18.5% in 2050, significantly higher than the 12.4% of the residential sector. The total cement stock of non-residential buildings in Chengdu will reach 157 Mt in 2035, exceeding the cement stock of residential buildings for the first time.

In comparison with residential buildings, non-residential buildings exhibit a distinct "small stock, high-intensity flow characteristic" in the metabolic processes of high-value secondary resources (e.g., steel and glass) and high embodied carbon materials. Although the total floor area of non-residential buildings is far smaller than that of residential buildings, the stock size of some high-value materials in non-residential buildings has approached or even exceeded that in the residential sector. Taking Chengdu as a case study, the proportion of steel stock in non-residential buildings to the total steel stock in urban buildings of the city will increase from 29.2% in 2000 (residential: ~2.58 Mt, non-residential: ~1.06 Mt) to 42.9% in 2035 (residential: ~65.59 Mt, non-residential: ~49.20 Mt), and further rise to 46.3% in 2050 (residential: ~72.26 Mt, non-residential: ~62.77 Mt). Xi'an shows a similar evolutionary trend, but the gap in absolute steel stock between the two building types is more pronounced: the steel stock in non-residential buildings will grow from ~17.99 Mt in 2035 to ~26.63 Mt in 2050, with a cumulative stock of approximately 361 Mt; over the same period, the steel stock in residential buildings will increase from ~35.36 Mt to ~40.67 Mt, with a cumulative stock of approximately 615 Mt. These data demonstrate that the steel use intensity per unit floor area of non-residential buildings is significantly higher than that of residential buildings.

At the same time, the glass stock has been gradually different since 2035. In 2050, the glass stock of non-residential buildings in Chengdu (about 2.38 Mt) is significantly higher than that of residential buildings (about 1.71 Mt). In general, although the "volume" of non-residential buildings is smaller than that of residential buildings, they occupy a core position in the metabolism of high carbon emission and high recycling value materials such as steel and glass and are the key areas of high-value resource recycling in the future urban circular economy strategy.

3.3. Construction Waste Resource Utilization Potential

3.3.1. Long-Term Evolution and Sources of Construction Waste (By Structure and Material)

In sharp contrast to the stabilization of new construction inflows, construction waste in both cities is projected to grow rapidly over the next three decades. Chengdu’s annual demolition waste volume will surge from approximately 5.05 Mt in 2020 to 29.44 Mt by 2050 (nearly a sixfold increase); Xi’an will see its volume rise from about 4.84 Mt to 15.90 Mt during the same period. Chengdu’s waste generation scale is approximately 1.7 to 2.0 times that of Xi’an. Particularly, between 2030 and 2050, as the first batch of early commercial buildings with shorter lifespans and buildings constructed during large-scale urban expansion reach their design lifespans, the rate of construction waste generation will significantly outpace the natural decline in new construction. Urban metabolism will fully transition from “incremental construction-dominated” to “stock renewal-dominated”. These projections indicate that construction waste volumes in both cities will continue to grow throughout the simulation horizon, showing no sign of peaking before 2050, even under the intensive development scenario, implying a sustained rather than transient pressure on waste management infrastructure.

By structure, although brick–concrete structures have significantly decreased in new construction, they will remain the primary waste source until 2030 due to the massive inertia of the existing stock. As shown in Figure 6a,b, the year 2029 marks a critical turning point. Prior to this, brick–concrete structures dominated waste outflow in both cities, presenting relatively low resource recovery challenges. However, starting in 2030, brick–concrete outflow begins to decline. Chengdu’s reinforced concrete outflow (approximately 4.57 Mt) will surpass brick–concrete (approximately 4.09 Mt) for the first time and permanently. Xi’an’s turning point occurs in 2032 (reinforced concrete outflow: 3.95 Mt; brick–concrete outflow: 3.70 Mt), slightly later than Chengdu’s. After 2035, reinforced concrete structures will become the dominant source of waste generation. The outflow volumes for reinforced concrete structures in both cities surpass the 10 million ton threshold in 2037 and 2044, respectively (accounting for over 60% of total outflow). By 2050, Chengdu’s reinforced concrete waste (14.67 Mt) will be 15 times that of brick–concrete waste (0.95 Mt) during the same period. Meanwhile, although steel structure waste remains relatively small in volume, its rapid growth rate creates an urgent need for separation technologies targeting high-strength metal components.

In terms of material composition (Figure 6c,d), the proportion of brick waste has plummeted from over 60% in the mid-20th century to approximately 15% by 2050, gradually replaced by the concrete matrix (cement, sand, and crushed stone), which will dominate by the 2040s (around 77% in Chengdu and 76% in Xi’an), providing a rich feedstock for high-quality recycled concrete aggregates. Additionally, as steel structures and reinforced concrete buildings are demolished, the proportion of scrap steel in waste streams will stabilize between 3.5% and 3.7%. Though relatively low, the massive volume (Chengdu’s scrap steel output reaching approximately 1.15 Mt by 2050) enables it to achieve an exceptionally high substitution rate for virgin iron ore.

Beyond structural and compositional differences, the outflow trajectories diverge markedly between residential and non-residential buildings (Figure 7). Residential structures remain the principal source of demolition waste throughout the horizon. By 2050, residential outflow will reach 19.15 Mt in Chengdu and 11.69 Mt in Xi’an, 1.86 and 2.78 times their non-residential counterparts (10.29 Mt and 4.21 Mt), broadly consistent with the residential-dominated waste pattern reported for the Chinese building stock at the national scale [47]. The substantially higher ratio in Xi’an indicates that its future waste burden will be more heavily concentrated in the residential sector, whereas Chengdu’s more balanced ratio reflects its stronger tertiary sector footprint.

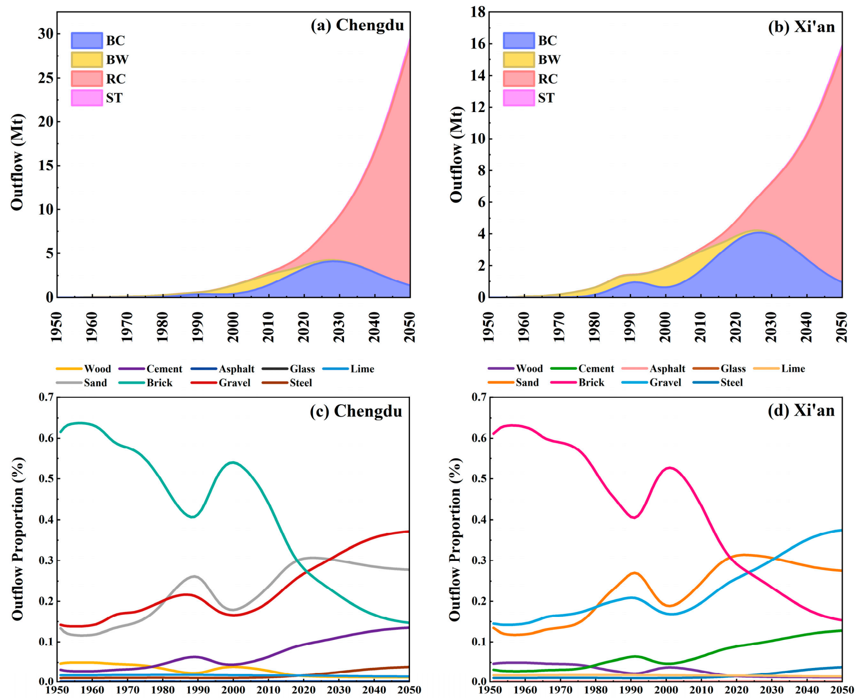

Figure 6. Sources and components of construction waste in Chengdu and Xi'an from 1950 to 2050: (**a**,**b**) amount of construction waste with different structures; (**c**,**d**) components of construction waste.

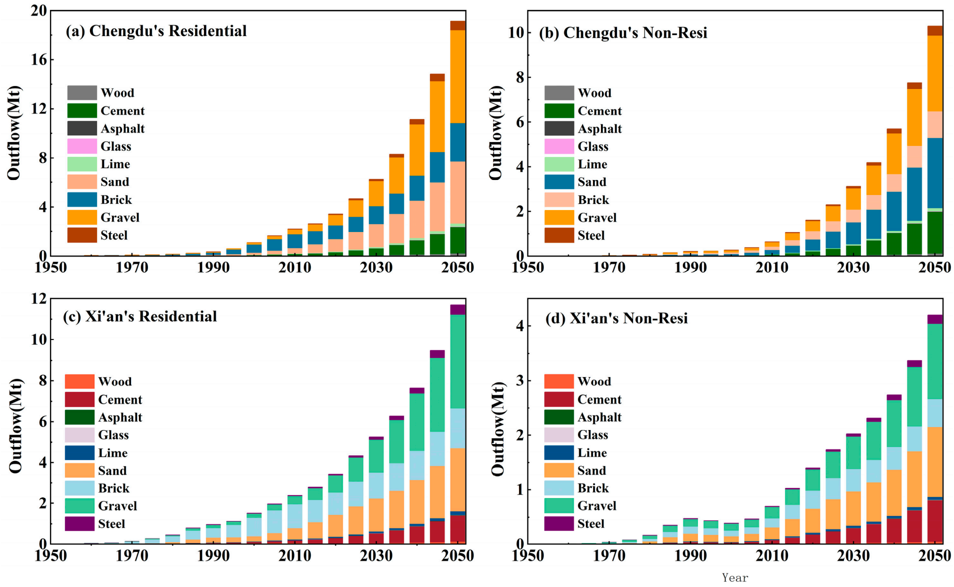

Figure 7. Heterogeneity in material outflow between residential and non-residential buildings in Chengdu and Xi'an from 1950 to 2050 (intensive development scenario): (**a**,**b**) Chengdu's residential and non-residential buildings; (**c**,**d**) Xi'an's residential and non-residential buildings.

The two sectors also exhibit distinct compositional profiles. Non-residential outflow consistently carries a higher share of high-strength binders. By 2050, cement will account for roughly 18% of non-residential outflow in both cities compared to only about 11% in the residential sector, while the concrete–aggregate complex (cement + sand + gravel) will constitute about 81% of non-residential outflow versus 77% of residential outflow. Conversely, brick, a legacy of pre-2000 masonry housing, remains markedly more prominent in residential streams (about 16% by 2050) than in non-residential streams (about 12%) [33]. Although the steel share converges across sectors (3.8–4.0% by 2050), the absolute scrap steel outflows from non-residential buildings remain substantial, corroborating their role as high-value secondary metal reservoirs [43]. These patterns suggest that residential demolition will generate large but relatively low-grade aggregate streams, whereas non-residential demolition produces smaller but more concentrated streams of high-value recyclables that justify selective pre-demolition dismantling protocols.

3.3.2. Secondary Resource Recovery Potential and Primary Material Substitution Effect

Construction waste represents a substantial secondary material resource. The following analysis quantifies the potential for recycled aggregates, cement components, and scrap steel to substitute for primary material demand, thereby reducing reliance on virgin resource extraction.

Concrete aggregates (sand and crushed stone) constitute the largest consumption of inert materials in construction activities. Without reuse, both cities face significant depletion of primary resources (e.g., Chengdu's virgin sand and gravel demand will peak at over 100 Mt around 2026). Under a 100% reuse scenario, from 2025 to 2035, as large numbers of brick–concrete structures enter demolition phases, the supply of recycled aggregates will steadily increase, potentially replacing 10–30% of new construction demand. After 2040, the convergence of sharply reduced new construction flows (due to per capita area saturation under intensive development models) and peak demolition flows will enable recycled supply to fully cover and consistently exceed new demand. By 2050, recycled sand and gravel volumes will reach approximately three times actual demand (3.9 times in Chengdu, 2.42 times in Xi'an) (Supplementary Material Figure S3a,b,e,f).

For high-carbon materials and high-value metals, the substitution effect of recycled resources is equally pronounced. Assuming an 80% recovery rate for cement components in waste concrete, the recycled supply will approach 100% virgin substitution by the late 2040s (reaching 97.55% in Chengdu by 2046 and 99.51% in Xi'an by 2049) (Table 2, Supplementary Material Figure S3c,g), theoretically meeting most cement demands for new construction. Furthermore, under a scenario of 90% scrap steel recovery, although the substitution effect is initially delayed due to low steel content in early brick–concrete structures, the substitution rate increases significantly after 2035 (Chengdu peaks at 68.9%, Xi'an at 45.23%). By 2050, annual scrap steel recovery in both cities will reach 1.15 Mt and 0.61 Mt, respectively. Long-term, as steel-structured buildings gradually enter their demolition cycle, the substitution rate for virgin steel demand will continue to rise (Supplementary Material Figure S3d,h). Strengthening secondary recycling of scrap steel from construction waste remains a key pathway for achieving green, high-quality development in the construction industry.

Table 2. Year of reaching key substitution rate milestones for recycled materials.

Material	**Reuse Rate**	**Chengdu**			**Xi'an**		
		50%	**80%**	**100%**	**50%**	**80%**	**100%**
Sand	100%	2034	2038	2039	2030	2035	2037
Gravel	100%	2035	2038	2040	2033	2036	2039
Cement	80%	2040	2044	2046	2040	2046	2050
Steel	90%	2047	/	/	/	/	/

3.4. Decomposition of Factors Influencing MS Change

Overall, during the study periods (1950–1975, 1976–1995, 1996–2010, 2011–2020), economic growth consistently emerged as the dominant driver of building stock expansion, contributing the largest share of stock change across most of the study periods. Urban population growth provided significant support, while the decline in material utilization intensity emerged as a key factor restraining disorderly expansion and reflecting improved development quality. The evolutionary trajectories of these drivers exhibited significant heterogeneity across different historical phases in both cities (Figure 8).

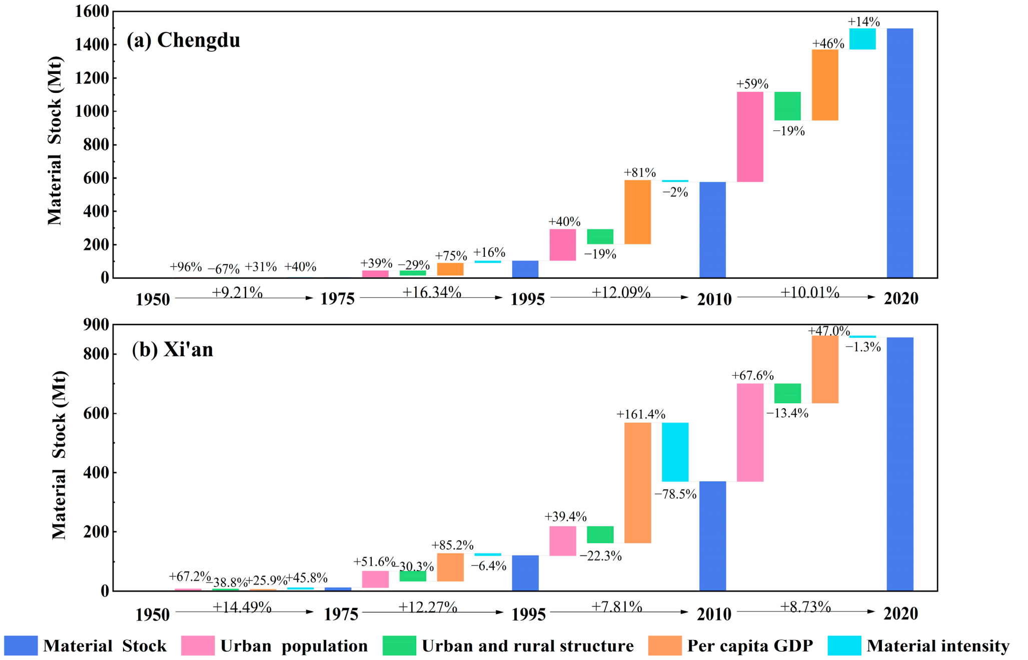

Figure 8. Decomposition results of Chengdu and Xi’an in four periods (1950–1975, 1975–1995, 1995–2010, 2010–2020).

Economic effects, represented by per capita GDP, consistently served as the most fundamental driver of building stock growth in both cities. The economic drivers in both cities followed a trajectory of “low-level start-explosive growth-high-level stabilization.” During the industrialization foundation phase (1950–1975) and the reform and opening-up exploration period (1976–1995), the contribution rate of economic effects rose to 74.5% (Chengdu) and 85.2% (Xi’an), respectively. The driving role of economic effects peaked during the initial phase of the Western Development Strategy (1995–2010). Xi’an’s economic contribution rate reached 161.4%, substantially exceeding Chengdu’s 81.5%. This notably high value, which exceeds 100% due to the offsetting negative contributions of other factors during the same period, indicates that GDP growth was the principal force sustaining stock expansion in Xi’an during this phase. As the economy entered the “new normal,” the contribution rates of economic effects for both cities retreated to around 46–47% (2011–2020). This reflects a gradual shift in their economic growth models, moving from extensive, high-speed expansion toward high-quality development and rational reorientation, under the Belt and Road Initiative and the National Central City strategy.

Scale effects (urban population size) form the foundation for building stock growth. From 1950 to 1975, Chengdu exhibited a classic “population growth drives building growth” pattern, with scale effect contributing as much as 96.0% (Xi’an: 67.2%). As urbanization deepened between 1996 and 2010, the relative contribution of the scale effect declined in both cities (to around 40%) due to the dilution effect of economic growth, though its absolute contribution remained substantial. Notably, from 2011 to 2020, influenced by the “talent recruitment wars” and relaxed household registration policies, the scale effect rebounded in both cities (Xi’an: 67.6%, Chengdu: 59.0%). The essential housing demand generated by new urban residents re-established the demographic dividend as a crucial force supporting the renewal of existing housing stock in western central cities.

The structural effect (urban–rural population structure) showed a negative contribution throughout the entire cycle in both cities. As urbanization rates surpassed the 70%

threshold, their contribution rate significantly narrowed during 2011–2020 (Xi'an: −13.4%, Chengdu: −19.0%). This indicates that the marginal impact of pure urban–rural population transfers on existing stock growth is diminishing. Future stock evolution will increasingly depend on natural population growth within cities and improvements in residential standards.

The intensity effect (material stock per unit of GDP) reflects the material dependency of urban development and represents the most divergent driver between the two cities. Xi'an's intensity effect turned negative starting in 1976 (−6.4% from 1976 to 1995) and reached −78.5% between 1996 and 2010, successfully decoupling economic growth from material consumption and demonstrating pronounced intensive development characteristics. Chengdu's intensity effect remained consistently positive (15–40% from 1950 to 1995). Although it briefly turned marginally negative (−2.4%) from 1996 to 2010, it regained positive territory (+13.7%) from 2011 to 2020—a stark contrast to Xi'an's −1.3% during the same period. This indicates that against the backdrop of "Park City" demonstration zone development and large-scale infrastructure upgrades, Chengdu's material input intensity for spatial expansion has remained high in recent years, with substantial investment in construction materials persisting.

4. Discussion

4.1. Sensitivity Analysis

To investigate the impact of various factors on the future prediction results of dynamic material flow analysis, explore potential fluctuation ranges, and determine the relative importance of each factor, a sensitivity analysis was conducted on all parameters using the control variable method. The results indicate that the population is the most critical sensitive factor influencing the system, directly determining the long-term accumulation scale of stock. Per capita building area primarily affects the flow segment, with its driving force on new construction inflows comparable to that of the population, while the average building lifespan is the single parameter exerting the greatest disturbance on waste outflow. Throughout this process, the sensitivity response trends of building floor area and material stock flow remain highly consistent. Consequently, extending building lifespans and slowing metabolic cycles through technological and managerial approaches represent the core pathway for reducing demolition waste generation and alleviating urban environmental burdens. Detailed data and analysis are presented in Table S3 and Note S2 of the Supplementary Materials.

4.2. Comparison with Other Studies

Independent long-term studies of building metabolism in western central cities remain scarce. To validate our results, we, therefore, benchmarked our 1950–2050 estimates for 1978–2020 against the Urban Product, Building, and Infrastructure Material Stocks (UPBIMS) dataset [32], the most comprehensive city-level benchmark for China, compiled from 1259 official yearbooks and bulletins using a bottom-up accounting approach. The comparison shows that the evolutionary trajectories of total residential and non-residential material stocks in Xi'an and Chengdu are broadly consistent with UPBIMS, while the discrepancies display a clear stage-dependent pattern. Deviations are larger before 1985, attributable mainly to sparse early statistics. About 55% of the UPBIMS records were imputed through interpolation or proxy variables [32] and were compounded in our model by the absence of reliable initial stocks and the high dispersion of material-intensity parameters for the then-dominant brick–wood structures. Deviations are smallest over 2000–2020, with relative errors of roughly 25% for residential and 35% for non-residential total stocks, well within the range reported in comparable studies (UPBIMS itself differs from existing Beijing and Shanghai estimates by approximately 8–46% in total stock [32]).

The slightly larger non-residential error stems from a widely acknowledged source of uncertainty: the long-standing absence of officially reported non-residential floor area in China, which must be inferred from residential-to-non-residential ratios [32]. Overall, the model is reliable over the core study period, lending robust support to our key findings on the double-peak inflow, stock saturation, and waste generation peak.

4.3. Policy Recommendations

Based on the above analysis, the following suggestions are put forward for the central cities in Western China:

1. Curb extensive demolition and rebuild renewal and shift toward whole lifecycle stock management. A regular inspection and maintenance system for existing buildings should be established, with demolition of structures that have not reached their design service life strictly controlled and “micro-renovation” encouraged to restore function and unlock the latent value of aging communities, consistent with the 2021 MOHURD Notice on Preventing Large-Scale Demolition and Reconstruction during Urban Renewal, which advocates small-scale, meticulous renewal [48]. On the supply side, long-life residential design approaches, emphasizing flexible layouts that can adapt to evolving household needs, should be promoted to extend functional service life from the design stage. Given the central role of population size and spatial standards in determining total stock volume, western Chinese cities may consider adopting per capita floor area as a binding planning indicator to guide spatial optimization and steer urban development toward an intensive pathway, thereby preventing the accumulation of underutilized vacant stock [49]. However, implementing strict lifespan extension policies requires overcoming entrenched demolition-oriented redevelopment incentives and addressing the financial interests of developers, which necessitates complementary regulatory reforms in land use and building codes. As Song et al. [50] demonstrate, even with technically closed material loops, deep decarbonization ultimately depends on demand-side controls of this kind.
2. Build dedicated capacity to dismantle and recycle reinforced concrete ahead of the waste surge. Both cities should develop concrete crushing, screening, and steel stripping technologies to supersede low-grade landfilling and backfilling, prioritizing the quality and yield of recycled concrete aggregates [51] and securing the industrial capacity to absorb the tens of millions of tons of hard waste expected around 2040. Given the large substitution potential of scrap steel and recycled aggregates, governments should mandate minimum recycled material ratios through green procurement for municipal and non-load-bearing projects. Complementing such top-down mandates, comparative evaluations of CDW recycling enhancement strategies suggest that low-cost, easily implemented operational measures, organizing temporary bins by construction zone, identifying activities that produce recyclable materials, and strengthening company recycling policies, offer the highest usability and should be prioritized in parallel [38,39]. Specifically, for high-value steel and glass concentrated in non-residential buildings (commercial, office), establish dedicated pre-demolition resource assessment and recovery mechanisms to ensure their prioritization for remelting processes rather than disposal in landfills. In practice, the high-quality recycling of reinforced concrete demands capital-intensive sorting and crushing facilities that many mid-sized Chinese cities currently lack. Public investment in regional treatment infrastructure and phased subsidy programs will be critical to bridging this gap.
3. Adopt tiered, city-specific management reflecting the two cities’ differing timelines. Chengdu, with its large stock and rapid turnover, should initiate large-scale recovery

facilities and explore a regional construction waste trading platform; Xi'an, still in the transitional window from brick–concrete to steel–concrete waste, should use this buffer to refine regulations and standards, prioritizing on-site disposal and ecological utilization of the debris and brick waste from urban village renovation. Additionally, given the high-frequency renewal and high-carbon material density of non-residential buildings (commercial offices and public structures), independent material tracking systems (e.g., BIM-based building material ledgers) should be established for non-residential buildings to enable pre-demolition resource assessment and prevent high-value materials from being mixed into undifferentiated demolition debris. Beyond pre-demolition accounting, BIM adopted at the design and pre-contract stages has been shown to curb waste at its source by mitigating design complexity, contract document errors, and frequent design changes [40], reinforcing the value of digital material management across the full building lifecycle. The feasibility of differentiated management between Chengdu and Xi'an ultimately depends on coordinated inter-departmental governance and standardized waste tracking systems, which are still under development in most Chinese cities.

4.4. Limitations

Although this study examines building metabolism in two western Chinese cities across four structural types, nine material categories, and both residential and non-residential sectors—while accounting for the temporal evolution of material intensity coefficients and building lifespans—several uncertainties remain. For example, the accounting covered nine bulk materials (e.g., sand, gravel, cement, steel, and brick) but excluded non-ferrous metals, such as copper and aluminum, which are widely used in building electromechanical systems and façades. As their unit economic value and embodied carbon are far higher than those of bulk aggregates and their recycling yields substantial environmental benefits, incorporating them would refine the assessment of secondary resource potential reported in this study. At the same time, we assume that the material intensity coefficients apply uniformly to both cities and that buildings within the same category share an identical structural composition; in reality, however, material intensity may vary across cities due to local construction practices, climatic adaptation requirements, and supply chain conditions. Future research can further improve the accuracy and foresight of urban-scale building material metabolism simulation by leveraging local construction cost databases, targeted field surveys, and multi-source big data to establish more accurate localized parameter databases.

5. Conclusions

By constructing a long-term dynamic material flow analysis (dMFA) model and LMDI driving force decomposition framework, this study systematically reveals the temporal and spatial evolution of building material metabolism in two western central cities, Xi'an and Chengdu, from 1950 to 2050. Material stocks in both cities followed an S-shaped growth trajectory, characteristic of the transition from "incremental expansion" to "stock saturation". However, notable inter-city heterogeneity emerged in both temporal trajectory and accumulation magnitude. Chengdu exhibited a stronger material accumulation capacity and faster metabolic rate, and its stock was expected to reach the peak around 2040 (about 2.2 billion tons) in the context of intensive development, and the total scale was about 2.05 times that of Xi'an (about 1.08 billion tons). From the perspective of material structure and functional composition, as building technology shifted from early brick–wood and brick–concrete structures toward reinforced concrete (RC) and steel structures (ST), the urban built environment has become increasingly material-intensive, resulting in a significant increase in the accumulated mass of cement and steel. Although non-residential buildings account for a smaller share of total floor area, their material intensity per unit area, particularly for steel and glass, is substantially higher than that of the residential sector, positioning them as the primary repositories of high-value urban mineral resources. In addition, the analysis of driving mechanism shows that economic growth is the core driving force of stock expansion in the historical cycle, but as urbanization enters the second half, stock growth is expected to gradually decouple from economic expansion, and future stock magnitude will be primarily constrained by the saturation thresholds of population size and per capita floor area, while the rate of material turnover will be governed by building lifespan. The key to promoting the green transformation of the construction industry in western central cities lies in the transformation from the traditional flow control to the full life cycle stock management. At present, the flow of new buildings in the two cities has shown a "double peak" downward trend, and the amount of construction waste will witness explosive growth after 2030 (the intensive development scenario will reach 29.44 Mt in Chengdu and 15.9 Mt in Xi'an in 2050). Urban managers should implement differentiated circular economy strategies. On one hand, proactive investment in concrete crushing, aggregate screening, and steel sorting technologies is needed to enhance the substitution rates of recycled aggregates and scrap steel for virgin materials, thereby establishing a closed-loop material cycle. On the other hand, given the high renewal frequency and elevated material intensity of non-residential buildings, dedicated material accounting systems and selective pre-demolition disassembly protocols should be established to prevent the downgrading of high-value resources. In parallel, promoting long-life residential design from the outset, combined with managed growth of per capita floor area, would fundamentally slow material turnover rates and reduce the resource and environmental burden on the urban system.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/buildings16132481/s1, Figure S1. Scenario settings of key parameters. Figure S2. Flow of residential and non-residential building materials in Chengdu and Xi'an from 1950 to 2050 (intensive development scenario). Figure S3. Material recycling potential under different reuse scenarios of cement, sand, gravel, and steel. Table S1: Average life of buildings with different structures in different years; Table S2: Material intensity (MI) for various types of buildings; Table S3: Sensitivity analysis results of each parameter; Note S1: Basis for setting saturation values across scenarios and underlying data sources for each parameter; Note S2: Sensitivity analysis. References [6,21,24,27,28,33,41,43–45,52–55] are cited in the Supplementary Materials.

Author Contributions: Conceptualization, R.C. and L.S.; methodology, R.C., L.S., C.D., and G.Z.; software, R.C. and C.D.; validation, R.C., G.Z., T.Y., and F.W.; formal analysis, R.C., C.D., and G.Z.; investigation, R.C., G.Z., T.Y., R.C., and X.Z.; resources, R.C. and L.S.; data curation, R.C., C.D., T.Y., and F.W.; writing—original draft preparation, R.C., L.S., and C.D.; writing—review and editing, R.C., and L.S.; visualization, R.C., F.W., and G.Z.; supervision, L.S., and X.Z.; project administration, L.S.; funding acquisition, L.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research is supported by the Nature Science Foundation of China (52500250), the National Science and Technology Major Project for Integrated Environmental Governance of the Beijing–Tianjin–Hebei Region (2026ZD1218603), the Open Research Fund of Key Laboratory of Eco-industry of Ministry of Ecology and Environment, the Chinese Research Academy of Environmental Sciences (2024KFF-01), the Shanghai Pujiang Program (22PJC052), the Natural Science Foundation of Shaanxi (QCYRCXM-2022-127), and the Youth Innovation Team of Shaanxi Universities.

Data Availability Statement: The original contributions presented in the study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: Authors Guohao Zhang, Ting Yang and Fufu Wang were employed by the company CSCEC Southwest Consulting Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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https://doi.org/10.3390/buildings16132481