Quantifying material stocks in long-lived products: Challenges and improvements for informing sustainable resource use strategies

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Review

Quantifying material stocks in long-lived products: Challenges and improvements for informing sustainable resource use strategies

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ABSTRACT

Material stocks in long-lived products require over half of the annual global resource extraction for their construction and maintenance, and lock in energy use through their technical and geospatial characteristics. A thorough understanding of material stocks is therefore essential to inform sustainable resource use strategies. However, despite substantial advances in material stock research in recent decades, their robust quantification remains challenging and bears considerable uncertainties.

We assess the (dis)agreement of material stock estimates from 32 recent studies across global, national, and urban scales, and propose recommendations for future work. Overall, we observe medium to high divergences between studies estimating the same material stocks. For end-use categories that aggregate multiple material stocks (e.g., buildings), most global-level estimates show divergences within 140 %. At the national level, most estimates for the USA diverge by <210 %, while those for China by <550 %. At the urban level, most estimates for Beijing fall within 90 %, and for Vienna, within 70 %. For low-income countries, non-residential buildings, and individual materials, the differences are often substantially higher, highlighting the need for an improved scientific basis for policy and planning.

These disparities arise from differences in system boundaries, methodology, data sources, definitions, and lack of data to capture the diversity of material stock types. To robustly inform sustainable resource use strategies, the scientific community and practitioners should systematically assess and report sensitivity and uncertainty, and reduce the latter through transparent documentation, model intercomparisons, consensus and open-access databases, enhanced data collection, and comprehensive quantification of material stocks.

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1. Improved understanding of material stocks is key for informing sustainable resource use strategies

Societal material stocks refer to materials accumulated in long-lived structures and products with lifespans greater than one year, such as buildings, infrastructure, machinery, vehicles, and appliances. These material stocks are central to shaping both societies' well-being and environmental pressures, as evidenced by their contribution to two-thirds of the Sustainable Development Goals (Thacker et al., 2019). On the one hand, these stocks provide essential services, such as shelter, mobility, and communication (Tanikawa et al. 2021). On the other hand, their construction and maintenance require over 50 % of annual global raw material extraction (Krausmann et al. 2017), contribute 60 % to greenhouse gas (GHG) emissions from material production (Hertwich 2021), and adversely impact biodiversity through soil sealing, habitat fragmentation, and mining in biodiversity-rich areas (Luckeneder et al. 2021; Meijer et al. 2018; Vilela et al. 2020; Maxwell et al. 2016). Additionally, the properties of these stocks —such as their operational efficiency, durability, and spatial organization— lock in energy and material flows over extended periods of time (Pauliuk and Müller 2014; Seto et al. 2016). Therefore, understanding the expansion, use, and maintenance of material stocks, as well as the interlinked resource flows, is key for informing supply- and demand-side strategies (Creutzig et al. 2018) that aim to improve societies' well-being while mitigating environmental pressures (Fig. 1; Creutzig et al. 2024).

Given the key role of material stocks in shaping both societies' well-being and environmental pressures, it is important to complement flow-based indicators —such as domestic material consumption or material footprints— with stock-based indicators to effectively guide sustainable resource use strategies (Tanikawa et al. 2021). Flow-based indicators have received considerable attention and are widely used as policy-relevant headline metrics. For example, the economy-wide Material Flow Accounting framework (ew-MFA) provides indicators on domestic material extraction and consumption, aligned with the System of Environmental and Economic Accounting (Fischer-Kowalski et al. 2011; UNEP 2023b). When combined with environmentally-extended input-output models, these data allow to calculate countries' material footprints (Lenzen et al. 2021; Lutter et al. 2016). Together, these standardized flow-based indicators inform national resource use policies (e.g., Takiguchi and Takemoto 2008; European Commission 2018; Miatto et al. 2024) and the Sustainable Development Goals 8 and 12 (UNEP-IRP 2019; UNSD 2022). However, to fully capture biophysical system dynamics —such as the time lags between material use in construction and waste outflows at stock demolition— a stock-flow consistent approach linking resource extraction and use, with stocks, waste, and emissions is required.

To achieve a stock-flow consistent approach, reliable information is needed regarding the types, uses, material composition, and spatio-temporal dynamics of material stocks (Nuss et al. 2022; Wuyts et al. 2022). This includes data on stock resource efficiency and lifetime to evaluate the required replacements and refurbishments (e.g., Serrenho et al. 2019; Kalt et al. 2022), their spatial and vertical organization to plan resource-efficient infrastructure and cities (e.g., Berrill et al. 2024; Rankin et al. 2024; Nicholson and Miatto 2024), their size and spatio-temporal demolition patterns to evaluate when, where and at what quality secondary materials become available for reuse (e.g., Schiller et al. 2017a, 2017b; Heeren and Hellweg 2019; Berrill and Hertwich 2021), and their projected growth to develop scenarios and strategies for future materials demand (e.g., Miatto et al. 2021; UNEP 2024; Rankin and Saxe 2024).

Research on stock-flow consistent approaches has advanced considerably in recent decades (Fu et al. 2021; Deng et al. 2023), yet substantial challenges in quantifying material stocks remain. While material stocks are increasingly studied across spatiotemporal scales and different end-uses, such as buildings and roads (Deng et al. 2023), their usefulness for policy-relevant monitoring and reporting can be improved. In academia, studies have assessed the environmental benefits of energy- and material efficiency measures that target material stocks (e.g., (Watari et al. 2022; Pauliuk et al. 2021; UNEP 2024). Within climate and risk communities, material stocks and flows are increasingly incorporated into Integrated Assessment Models to capture material-energy-GHG emission feedbacks. Such models are used in IPCC assessments (IPCC 2023), by the financial sector (Richters et al. 2023), and to inform climate negotiations (Creutzig et al. 2024; Ünlü et al.

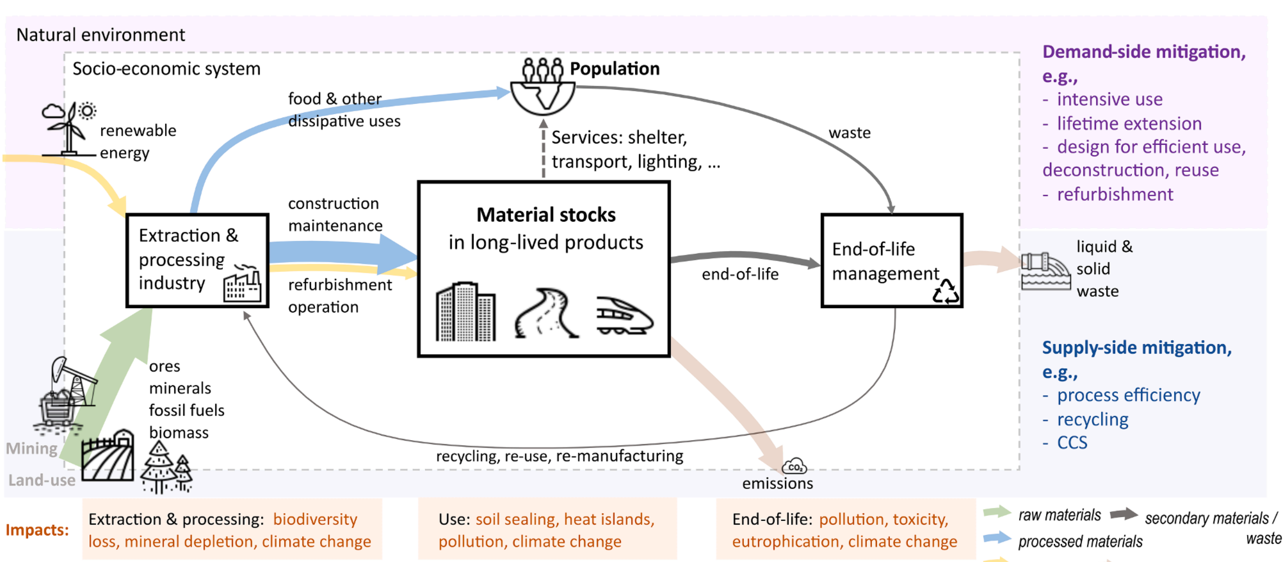

Fig. 1. Schematic illustration of the key role of material stocks for both societies' well-being, environmental pressures and impacts. Material stocks accumulate when material flows are transformed into products for human use, providing multiple essential services to society. The construction and maintenance of these stocks require more than half of the global annual resource extraction and drive emission and waste flows, resulting in a range of environmental pressures and impacts. While these pressures can be mitigated through both supply- and demand-side measures, the consistent evaluation of their mitigation potentials requires a systemic perspective on resource use. This perspective begins with a harmonized system boundary (for example used in economy-wide material and energy flow accounting) that links raw material and energy extraction from mining, land-use, and renewable energy generation, to the societal uses of materials processed into products, along with the associated waste and emissions.

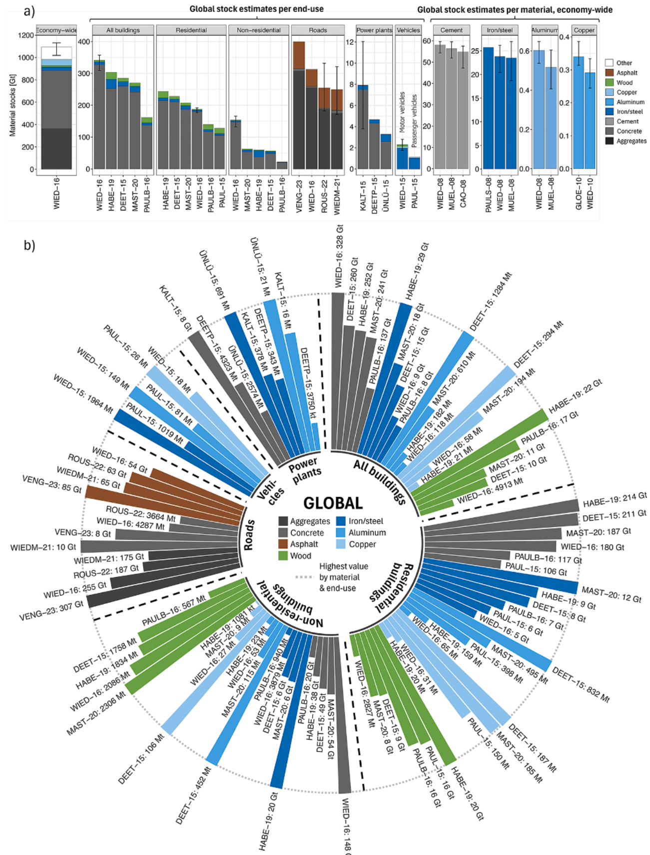

Fig. 2. Divergences in estimates of global material stock end-use types for eight major bulk materials in the years 2008–2022 from various sources. The two-digit number behind the study source indicates the year for which material stocks are estimated. (a) Sum of stocks per end-use for several overlapping bulk materials, and stocks for economy-wide use of cement, iron/steel, aluminum and copper. Whiskers represent reported divergences within-models (see SI-1 for details on whiskers' data). Vehicle stock estimates cannot be directly compared due to different scopes: all motor vehicles (Wiedenhofer et al. 2024b) vs. passenger vehicles (Pauliuk et al. 2021). When concrete, cement, and aggregates are presented in a stacked format, aggregates and cement refer to those used in applications other than concrete; (b) Global material stocks by end-use type and individual material. Stocks by material and end-use are normalized to the highest value to fit all categories in one graph. This does not mean that this value is the best estimate. A direct comparison across end-uses and materials in panel (b) is not possible (for this, please refer to the numerical values in the panel, panel (a), or the supplementary data SI-2). Sources – dynamic top-down: CAO: (Cao et al. 2017), GLOE: (Glöser et al. 2013), MUEL: (Müller et al. 2013), PAULS: (Pauliuk et al. 2013), WIED: (Wiedenhofer et al. 2024b); dynamic bottom-up, statistics-based: DEET (buildings): (Deetman et al. 2020), DEETP (power plants): (Deetman et al. 2021), KALT: (Kalt et al. 2021), MAST: (Mastrucci and van Ruijven 2023), PAUL: (Pauliuk et al. 2021), PAULB:(Pauliuk et al. 2024a), ÜNLÜ: (Ünlü et al. 2024); static bottom-up, remote-sensing/geographic databases: HABE: (Haberl et al. 2024), ROUS: (Rousseau et al. 2022),WIEDM: (Wiedenhofer et al. 2024a), VENG: (van Engelenburg et al. 2024). The data for plots is provided in SI-2.

2024). In policy and business, the use of material stock research is still rare, although secondary resource cadasters for urban mining are increasingly attracting interest (Wiener Stadtwerke 2024; UBA 2015; Madaster 2024). Despite these advancements, consistently and robustly quantifying material stocks and their associated material flows remains challenging, particularly at large scales, such as national economies or globally. This is due to data gaps, inconsistent data sources, lacking uncertainty information (Lanau et al. 2019; Deng et al. 2023) and only rudimentary standardized procedures and databases compared to methodologies like ew-MFA or Life Cycle Assessment (ISO 14044; Brunner and Rechberger 2016; Wernet et al. 2016).

Owing to these challenges in quantifying material stocks, studies evaluating the benefits of sustainable resource use strategies currently rely on estimates of historical material stocks with considerable uncertainties and differences across studies. These discrepancies are evident for the size, age composition, lifetime, and material intensity of stocks. Given the long-term dynamics of stocks and flows, such differences lead to disparate assessments of the timing and scale of stock demolition, associated waste flows, and material requirements for maintenance and new construction. As a result, these diverging material stock estimates introduce uncertainty into the assessment of environmental benefits of materials-focused mitigation strategies, which limits their usefulness for planning and policy development. To improve the comparability of models and support the robust selection of resource management strategies, it is essential to gain a deeper understanding of the reasons behind divergent material stock estimates, such as the use of assumptions and proxy data.

This review seeks to address the challenges of quantifying material stocks by comparing recent studies on bulk material stocks (e.g., concrete, timber, and steel) across three spatial scales. It investigates the extent of diverging stock estimates and the factors contributing to these discrepancies, and explores avenues for future improvement. We begin by describing the different methods and data used to quantify material stocks, followed by an analysis of diverging estimates of historical material stocks from 32 recent studies at the global, national, and urban levels. These studies cover seven major end-use categories—ranging from all buildings, residential buildings, and non-residential buildings, over roads to vehicles, power plants, and machinery. By examining the underlying reasons for discrepancies in stock estimates, this review aims to provide a roadmap for improved material stock quantification to support effective and sustainable resource use strategies.

2. Literature selection and methodology for comparing material stock estimates

2.1. Literature selection

We selected recent studies quantifying bulk material stocks for at least one historical year, primarily at the global and national levels, including some urban comparisons. We derived studies in addition to works already covered in Lanau et al. (2019), using Google Scholar, citation snowballing and the authors' expertise. Additionally, we included a few highly cited studies published earlier. Our selection comprises 32 studies, published between 2006 and 2024, which provide data on material stocks of economy-wide bulk materials or major end-uses such as buildings and roads. We did not aim for a comprehensive review but to capture a snapshot of the state-of-the-art to identify challenges and opportunities for improvement in estimating material stocks and flows. Of the 32 studies, 15 are *static bottom-up* models, most offering a single-year snapshot; 12 are *dynamic bottom-up* models, eight of which model prospective scenarios based on historical stock estimates; and five are *dynamic top-down* models, which assess the historical development of stocks. For the allocation of these studies across the different modelling approaches, please refer to the captions of Figs. 2–4.

2.2. Methodology for comparing material stock estimates

We compared the divergences in material stock estimates both *within* and *between* the 32 studies/models. *Within* a single study/model, divergences reflect the difference between minimum and maximum stock

(a) coefficients of variation between estimates of different studies, stock values for USA (b) and China (c)

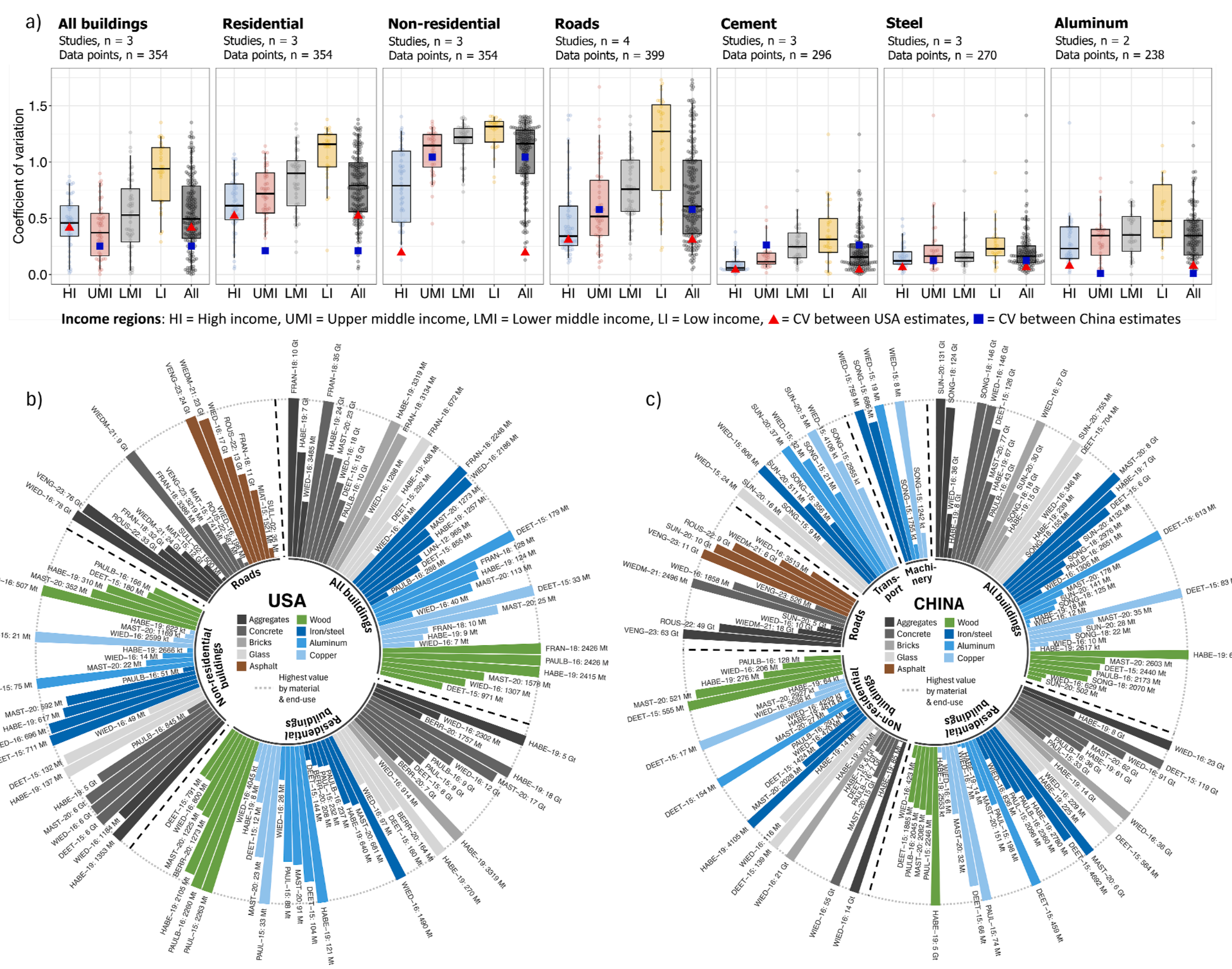

Fig. 3. Divergences in estimates of country-level stock end-use types by material for 2002–2021 from various sources. The two-digit number behind the study source indicates the year for which stocks are estimated. (a) swarm and box plots of the coefficients of variation (standard deviation divided by mean) of material stock estimates between studies with a comparable material scope and region-year-material/end-use correspondence for buildings (over the sum of the materials concrete, iron/steel, aluminum, copper, wood, glass in Mastrucci and van Ruijven 2023; Haberl et al. 2024; Wiedenhofer et al. 2024b), roads (over the sum of the materials aggregates, asphalt, concrete in Wiedenhofer et al. 2024b; Wiedenhofer et al. 2024a; Rousseau et al. 2022), and economy-wide cement, steel and aluminum material stocks (Cao et al. 2017; Müller et al. 2013; Wiedenhofer et al. 2024b; Pauliuk et al. 2013); boxplots show the interquartile range (IQR): median as thick line, the 75th/25th percentile (Q3/Q1) as box range and the 5/95th percentile as whiskers. The dataset includes ~3000 data points categorized by the 2016 World Bank Income Groups with 2–4 region-year-material/end-use data points for comparison. For studies that report different estimates within models, the best guess / mean estimate was used to compare between studies. The coefficients of variation for the USA and China are highlighted in red and blue, respectively, for correspondence to panels b-c. (b) material stock estimates for the USA by material and end-use, (c) material stock estimates for China by material and end-use. Sources (in addition to listed in Fig. 2): dynamic bottom-up, statistics-based: BERR: (Berrill and Hertwich 2021), MIAT: (Miatto et al. 2017c), SONG: (Song et al. 2021), SUL: (Sullivan 2006), SUN: (Sun et al. 2023); static bottom-up, remote-sensing/geographic databases: FRAN: (Frantz et al. 2023), LIAN: (Liang et al. 2023). For U.S. road bitumen and cement stocks in (Miatto et al. 2017c), we multiplied by factor 20 and 6.7 respectively, to compare with asphalt and concrete stocks of other studies (we deducted the thereby added aggregate use in asphalt and concrete from the value for aggregate stocks to keep overall stock levels constant). The data for plots is provided in SI-2.

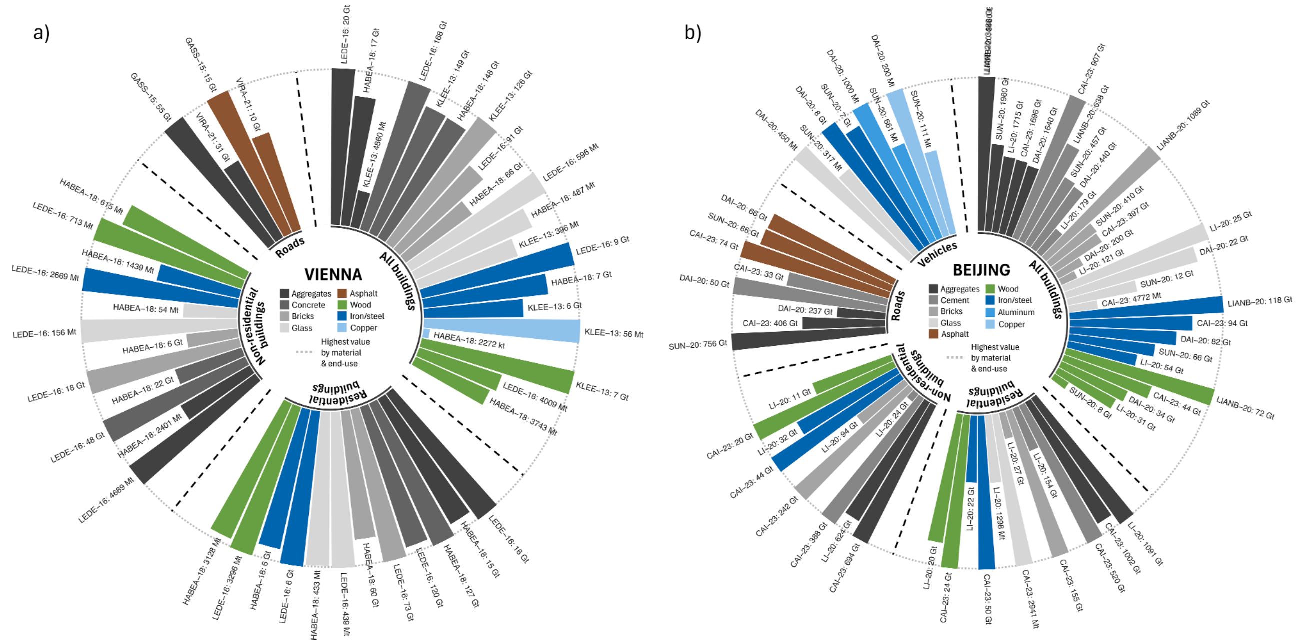

Fig. 4. Divergences in estimates of urban material stocks by end-use types from different studies for Vienna (a) and Beijing (b). Sources: (a) Vienna – static (multi-year) bottom-up, statistics-based: GASS: (Gassner et al. 2020), VIRA: (Virág et al. 2022), static (multi-year) bottom-up, remote-sensing/geographic databases: HABEA: (Haberl et al. 2021), LEDE: (Lederer et al. 2021), KLEE: (Kleemann et al. 2017a); (b) Beijing – static (multi-year) bottom-up, statistics-based: DAI: (Dai and Yue 2023), LI: (Li et al. 2023), static bottom-up, remote-sensing/geographic databases: CAI: (Cai et al. 2024), static (multi-year) bottom-up, remote-sensing/geographic databases: LIANB: (Liang et al. 2023), dynamic bottom-up, statistics-based & remote-sensing/geographic databases: SUN: (Sun et al. 2023). The spatial boundaries of the study of (Cai et al. 2024) were adjusted to fit Beijing city boundaries. The data for plots is provided in SI-2.

estimates based on different model assumptions (see SI-1). *Between* different models/studies, divergences compare stock estimates of the same end-use type and material scope. To quantify these differences, we calculated factor differences across different estimates for the same material stocks at global, national, and urban scales (Eq. (1)), which can also be expressed as a percentage difference (Eq. (2)):

$$\textit{factor difference} = \frac{\textit{maximum estimate}}{\textit{minimum estimate}} \tag{1}$$

$$\textit{percentage difference}\ (\%) = \frac{\textit{maximum estimate}}{\textit{minimum estimate}} - 1 \cdot 100\% \tag{2}$$

For example, we compared the summed material stocks of concrete and asphalt in the end-use roads *between* two studies, or stocks of individual materials (e.g., asphalt) in this end-use. To summarize the divergences across the various end-uses and materials, we additionally calculated the median of factor differences over these groups.

For nine studies providing global, country-level material stocks, we further calculated the coefficient of variation (CV) for comparable combinations of country/end-use and country/material that matched *between* studies (see Fig. 3 caption for details, Eq. (3)):

$$CV = \frac{\textit{standard deviation}}{\textit{arithmetic mean}} \tag{3}$$

The CV is a dimensionless measure of *dispersion* that normalizes divergences *between* studies and makes them comparable across different groups (e.g., across various end-uses). The CV measures the *precision* of the estimates — i.e. how closely the estimates align (which does not imply their *accuracy*). A CV of zero indicates perfect precision, with dispersion increasing (and precision decreasing) as the CV rises. For example, we can infer that the overall material stock estimates for non-residential buildings (CV=1.2) are more dispersed than those for all buildings (CV=0.5). For further methodological details, please see SI-1.

Because studies report data for different historical years, we compared the most recent and closest available years to assess how much their estimates align. Given the long-term accumulation of material stocks in many of the countries examined, we do not expect the comparison of slightly differing years to substantially affect the observed alignment, with other sources of uncertainty playing a more dominant role. This is supported by the alignment observed in the few studies that provide historical time series. For example, factor differences for the sum of all investigated materials (Eq. (2)) over a five-year span differ by 20 % for the globe between 2011–2016 (Wiedenhofer et al. 2024b), and by 18 % for China between 2013–2018, which developed particularly fast in the past decades (Song et al. 2021, see data supplement). These temporal differences *within* studies are much smaller than most of the divergences identified *between* studies (see Section 4).

3. Approaches and progress in material stock research

Material stock research has achieved extensive coverage of various temporal and spatial scales, as well as end-uses such as buildings, roads, and machinery, utilizing diverse methods and data sources (Lanau et al. 2019; Fu et al. 2021; Deng et al. 2023). Material stocks are quantified through Material Flow Analysis (MFA), which operates in *static* or *dynamic* models employing either *top-down* or *bottom-up* approaches (Müller et al. 2014; Lanau et al. 2019; Wiedenhofer et al. 2019). *Static* MFA provides a snapshot of the system at a specific time, whereas *dynamic* MFA assesses system behavior over periods of time. *Top-down* MFA calculates stocks from the accumulation of net inflows (consumption less discard, the latter based on lifetime assumptions), whereas *bottom-up* MFA directly counts products or functional units and multiplies them with material intensities (Müller et al. 2014; Lanau et al. 2019). In dynamic MFA, the terms *stock-driven* and *inflow-driven* MFA refer to the type of exogenous data used to calculate stocks and flows, respectively. (Wiedenhofer et al. 2019).

An extensive review by Lanau et al. (2019) found that approximately half of the material stock studies published until 2018 employed top-down models, all of which were dynamic, while most bottom-up models were static. Less common approaches are discussed in Chen and Graedel (2015).

Recent advances in each approach include:

Top-down studies using material flow estimates derived from statistics on production, trade and consumption over several decades to calculate material stocks. They can cover all countries worldwide, long time spans, all major bulk- and several specialty materials, and economy-wide end-uses (e.g., Cao et al. 2017; Wang et al. 2018; Rostek et al. 2022; Wiedenhofer et al. 2024b). However, these studies rarely go below country-level resolution and often provide aggregate stock totals for individual materials across all end-uses. While some top-down studies distinguish stocks by end-use types, their resolution remains limited (Wiedenhofer et al. 2024b). Some of these studies assess strategies for mitigating material use and GHG emissions (e.g., Watari et al. 2022).

Bottom-up studies using statistical data on functional or product units to provide detailed assessments of specific end-uses, such as residential and non-residential buildings, passenger vehicles, or electricity infrastructure (e.g., Deetman et al. 2020; Deetman et al. 2021; Kalt et al. 2021). Due to scarce statistical data, these studies typically model only a single historical year and focus on specific end-use types. Sub-national assessments are common (Wuyts et al. 2022), with an increasing number of studies achieving global coverage, though often distinguishing only 20–25 countries or world regions for buildings. Several studies dynamically assess material- and energy efficiency strategies (e.g., Pauliuk et al. 2021; Zhong et al. 2022; Song et al. 2023).

Spatially-resolved bottom-up studies deriving functional or product units from 'big data', including remote-sensing (aerial photos, laser scanning, satellite images, nighttime lights) *and geographic databases* (volunteered geographic information, cadastral / survey data). They quantify materials in the built environment with high spatial resolution and coverage, sometimes providing component-level information (Dai et al. 2024), though often for a single year (e.g., Peled and Fishman 2021; Frantz et al. 2023; Rousseau et al. 2022). This approach can also be applied to historical maps to track the development of built environment stocks over time, with some remote-sensing studies offering time-series data too (e.g., Li et al. 2022; Schug et al. 2023). Different data sources offer varying spatiotemporal coverage and resolution, and geographic and thematic completeness. Therefore, they are often combined to maximize information. For example, Sentinel satellite data has been used to quantify various building properties, while Open Street Map has been used for road networks (e.g., Haberl et al. 2021; Cai et al. 2024; van Engelenburg et al. 2024), or nighttime light intensity has been connected with the intensity of material stocks (e.g., Liu et al. 2023; Peled and Fishman 2021). Spatially explicit scenario-modelling that dynamically assesses future material stocks is still rare (e.g., Heeren and Hellweg 2019).

4. Estimates of the same material stocks often show multiple factors difference

At the global level, we compared 16 studies on major material stock end-uses covering the years 2008 to 2022. Five of these studies employed a top-down approach, while 11 used a bottom-up approach (see Section 3 for an explanation of methods and Fig. 2 caption for study specifics).

A comparison across material stock end-uses reveals that buildings and roads dominate economy-wide material stocks by mass, with aggregates, concrete and asphalt being the quantitatively most important materials (Fig. 2a). In contrast, motor vehicles and power plant stocks represent a minor proportion of economy-wide stocks by mass but contain substantial amounts of metals. Other sectors — including civil engineering, machinery, other transport, textiles, and consumer products — are rarely studied at global level (also applies to literature beyond this study). One economy-wide study by some of the authors suggests that approximately 23 % of global economy-wide material stocks in 2015 are contained in those 'other' uses (Wiedenhofer et al. 2024b).

When examining the alignment of global stock estimates (Eq. (1)), we observed moderate to high divergences both *within* and *between* models. Divergences within models tended to be smaller than those observed between models. *Within* models (Fig. 2a, whiskers), estimates of economy-wide stocks for specific materials showed median divergences of factor 1.2, with ranges from factor 1.1 for cement to factor 1.5 for aluminum. Estimates for specific stock end-uses, which consist of multiple materials, exhibited median divergences of factor 1.5, ranging from factor 1.1 for residential buildings to factor 3.2 for power plants. *Between* models, around 80 % of the estimates for specific stock end-uses were within a divergence of factor 2.4 (140 % difference, Eq. (2)), with the median divergence at factor 2.1. Divergences ranged from factor 1.6 for roads to factor 7 for non-residential buildings (Fig. 2a). Estimates for both specific stock end-uses and materials (Fig. 2b) showed median divergences of factor 3.9, ranging from factor 1.6 for asphalt in roads to factor 100 for copper in non-residential buildings.

At the national level, we compared 13 studies for the USA (12 bottom-up, 1 top-down) and 11 studies for China (10 bottom-up, 1 top-down) covering the years 2012 to 2022 (Fig. 3b-c). As with the global level, we found moderate to high divergences both *within* and *between* models. *Within* models, two studies (Rousseau et al. 2022; Wiedenhofer et al. 2024a) provided estimates for road stocks, which exhibited *within*-model divergences ranging from factor 1.6 to factor 1.9 for the sum of aggregates, asphalt, and concrete (see data supplement for Fig. 3b). *Between* models, around 80 % of the estimates for specific stock end-uses were within a divergence of factor 3.1 (210 % difference) for the USA and factor 6.5 (550 % difference) for China. The median divergences were at factor 2.4 (USA) and factor 3.4 (China), ranging from factor 1.1 for machinery in China to factor 7 for non-residential buildings in both the USA and China (data supplement Fig. 3b). Estimates for both specific stock end-uses and materials (Fig. 3b-c) showed median divergences of factor 4.5 (USA) and factor 6.5 (China), ranging from factor 1.1 for iron & steel in Chinese machinery to factor 260 for copper in Chinese non-residential buildings.

Additionally, nine studies provided national-level data for a wide range of countries. For these, we assessed the dispersion of material stock estimates *between* studies by calculating the coefficient of variation (CV, Eq. (3)) for end-uses and World Bank income groups (see Section 2.2). We observed the highest dispersion for low-income countries, non-residential buildings, and economy-wide aluminum stocks (Fig. 3a). For end-uses, *between*-model divergences showed a median CV ranging from 0.5 (all buildings) to 1.2 (non-residential buildings). For economy-wide material stocks of specific materials, the median varied from 0.2 (cement) to 0.4 (aluminum). Notably, divergences increased from higher to lower income groups.

At the urban level, we compared five bottom-up studies each for Vienna and Beijing, covering the years 2013 to 2023 (Fig. 4). We observed smaller *between*-model divergences for end-uses (sum of overlapping materials) compared to those at the national to global levels, although divergences for specific materials were still notably high. Around 80 % of urban estimates for specific stock end-uses, were within divergence of factor 1.7 (70 % difference) for Vienna and factor 1.9 (90 % difference) for Beijing (see data supplement for Fig. 4a-b). The median divergences were at factor 1.2 (Vienna) and factor 1.5 (Beijing), ranging from factor 1.04 for Viennese residential buildings to factor 2.7 for roads in Beijing. Estimates for both specific stock end-uses and materials (Fig. 4a-b) exhibited median divergences of factor 1.6 (Vienna) and factor 2.1 (Beijing), ranging from factor 1.01 for glass in Viennese residential buildings and up to factor 25 for copper in Viennese buildings. Due to the limited scope of our assessment, no general conclusions can be drawn about divergence trends across scales.

The observed patterns align with our expectations, showing greater divergences *between* models than *within* models, as well as higher divergences for low-income countries compared to high-income countries, and for non-residential buildings compared to residential buildings. These patterns can be attributed to a broader range of input data used

Table 1
Types and examples of uncertainty and variability (Huijbregts (1998); Laner et al. (2014, 2016)) along the iterative steps in Material Flow Analysis (adjusted from Brunner and Rechberger (2016)). (a) Aleatory uncertainty from natural variability; (c) epistemic uncertainty from choice uncertainty, (m) model uncertainty, (p) parametric uncertainty. The sources of uncertainty in square brackets [] are not applicable nor further discussed here.

Iterative steps of Material Flow Analysis (MFA) & guiding questions to assess uncertainty	Sources of uncertainty	Specification & example for Material Flow Analysis models
Step 1. Problem, system & model definition	- natural variability (a)	+ natural variability of products in type, age, size, material, function and local context needs to be considered in modelling, e.g., because intensity of different materials in wall and frame of ~740 thousand U.S. single-family houses varies between 5–27 % and 8–91 % respectively (Saxe et al. 2020), or the material intensities of roads varies within U.S. regions (Frantz et al. 2023), and even within a small geographic area like Toronto (Kloostra et al. 2022)
+ Do model and system boundaries align with the problem of interest? + Do system boundaries affect decision-making? + How much natural variability can be expected for system components? + Does model structure affect conclusions?	- choice of system boundary (c)	+ choice of which materials, products and processes to include and which unit of measurement to use, e.g., because in/exclusion of ancillary facilities such as ventilation systems in material stock assessment of roads explains 20 % of divergences between results of two studies (Guo et al. 2014; Huang et al. 2017; Lanau et al. 2019) + definition of system boundaries is not trivial, e.g., for infrastructure which is an agglomeration of multiple sub-products (Saxe et al. 2020). Currently system definitions are partially implicit and not reported, e.g., for material intensity and material flow data (Heeren and Fishman 2019; Streeck et al. 2023).
	- model structure (m)	+ formal mathematical implementation, e.g., using Lognormal-, Weibull distributions or Kaplan-Meier functions for estimating buildings' lifetimes, survival and demolition (Miatto et al. 2017b; Guo et al. 2021; Bradley and Kohler 2007)
Step 2. Input data: inventories, material intensities, transfer coefficients, uncertainty characterization + In how far does the study data represent natural variability of parameters? + Can the study prioritize use of local and recent studies for parameters? + Are data sources incomplete or inaccurate? + Is sufficient information for uncertainty characterization available? Semi-quantitative uncertainty evaluation can be an option too (Laner et al. 2016) + Would the use of different input data sources affect results?	- lack of representative data for natural variability (p)	+ temporal: missing data on temporal variability of functional and product units, material intensities (Fishman et al. 2024), age-structure (Guo et al. 2021; Milojevic-Dupont et al. 2023), lifetimes (Wiedenhofer et al. 2024b), end-use shares (Streeck et al. 2023), demolition and recycling rates (Wiedenhofer et al. 2024b), structural-type shares + spatial: missing data on spatial resolution of functional or product units, material intensities (Fishman et al. 2024), material flows (Plank et al. 2022b, 2022a) especially for the Global South and rural areas (Mastrucci et al. 2023) + technological: missing data on distinction of (building) construction types (Fishman et al. 2024), material flow end-use (Streeck et al. 2023) + studies on parameter variance and representativeness are scarce (Fishman et al. 2024) + examples: - current material intensity data for buildings is based on few sources, spread throughout individual literature studies, geographically biased towards Global North, technically based on case-studies of individual or a sample of a few buildings referring to the context of a particular city, on construction manuals, or archetypical buildings (Heeren and Fishman 2019; Röck et al. 2023; Fishman et al. 2024) - road material intensities derived from construction guidelines/standards may not be representative of actual road construction (Grossegger et al. 2024) - high variance within products even of the same sub type "e.g. high rise residential, or multi-unit low rise" due to heterogeneity in design, material selection and construction both within and between locations (Arceo et al. 2023; Rankin et al. 2024)
	- incomplete data (p)	+ use of indicators not representing the defined product flow or stock of interest leading to over- or underestimation, e.g. using floorspace indicator for conditioned floorspace which excludes attics and stairways to quantify total material stocks of a building (Schiller et al. 2019), as well as including/excluding vacant buildings; U.S. floorspace estimates from statistics and remote-sensing diverge by factor 3 (Arehart et al. 2021) + some temporal parameters are impossible to accurately estimate due to insufficient passage of time, e.g., building lifetime estimates are typically 'right-censored', an issue which is greater for more recently built buildings. If some of a cohort of buildings remain undemolished, it is not possible to estimate the average lifetime or lifetime distribution parameters, because the time of demolition of the remaining buildings is not yet known (Bradley and Kohler 2007) + functional or product units derived from remote sensing or GIS databases can be incomplete with substantial regional variability in geographic completeness (Barrington-Leigh and Millard-Ball 2017; Zhou et al. 2022), but also thematic completeness of associated attributes (e.g., pavement types, (Frantz et al. 2023))
	- inaccurate data (p)	+ data not accurately representing measurement of indicator, e.g. through poor quality of statistical reporting of material extraction, production and trade for non-metallic minerals (Miatto et al. 2017a), measurement error for building height (Cai et al. 2023; Frantz et al. 2021), footprint or building type (Haberl et al. 2021), opaque and ambiguous documentation (e.g., of material intensities (Fishman et al. 2024)), and reported road lengths from statistics affected by methods used for estimation (Grossegger et al. 2024) + deviation between records/estimates and what was actually used in construction (e.g., 38 % more concrete being used in bridge substructures than shown in drawings, (Olanrewaju et al. 2022))

(*continued on next page*)

Table 1 (*continued*)

	- uncertain uncertainty (p,c)	+ lack of data on uncertainty resulting in assumptions and arbitrary choices of uncertainty distributions and relations of model parameters (Huijbregts 1998; Laner et al. 2014)
	- [disagreement] (c)	+ 'There is no consensus among scientists (opposing views), typically because of a lack of data.' (Laner et al. 2014; Morgan et al. 1990) + *e.g.*, disagreement between remote sensing products (Chakraborty et al. 2024)
	- [unpredictability] (p)	+ 'Uncertainty is irreducible in principle as a result of indeterminacy (i.e., practical unpredictability)' (Laner et al. 2014; Morgan et al. 1990), e.g. for parameters in prospective assessments + one-off or few-off nature of large products means that it is hard to predict in advance the degree of uncertainty (Saxe et al. 2020)
Step 3. Modelling: combine data & quantitative model, uncertainty propagation + If local and recent studies cannot be used to inform parameters, can conversion factors be applied to spatiotemporally misaligned data? + How do approximated parameters, assumptions and aggregation affect results? + If uncertainty could be characterized, how does uncertainty propagation affect results? + If uncertainty could not be characterized, sensitivity analysis should be conducted as fallback option	- approximation of missing parameter data (p,m,c)	+ *e.g.*, extrapolating lacking data on wood material intensity of a building for years before 1980 by using datapoint from 1980 for all prior years (e.g., for some parameters in (Pauliuk et al. 2021)); extrapolating lacking data on nonresidential building material intensity by using those from another country (Lanau and Liu 2020); use of single values of ceiling-to-ceiling and roof height in calculations of building volume from remote-sensing data (Milojevic-Dupont et al. 2023; Peled and Fishman 2021) and layer thickness for road surfaces (Grossegger et al. 2024) + *e.g.*, extrapolate from available water infrastructure data in some cities to estimate infrastructure in others (Rankin and Saxe 2024) + *e.g.*, use data available from specific countries to extrapolate at regional level and make up for data gaps in other countries
	- tailor available data to fit system definition (p,m,c)	+ aggregation of real-world granularity underlying system resolution due to lacking representative data, e.g., aggregation of material intensities across construction archetypes (Ortlepp et al. 2018; Lanau et al. 2019) and spatial scales (Kloostra et al. 2022) leading to inaccurate assessment
	- [disagreement]	+ see same category above
Step 4. Interpretation & communication + Are workflows and results transparently documented (ideally open-access)? + Do procedures and definitions refer to established frameworks? + Are uncertainty/sensitivity communicated to facilitate decision-making?	- inaccurate communication (p)	+ *e.g.*, linguistic imprecision by use of ambiguous material labels (Heeren and Fishman 2019), or differently defining 'dissipated stock' term (Lanau et al. 2019)

across models, as along with the limited research focus on low-income regions and non-residential buildings compared to high-income regions, residential buildings, and roads. However, only seven out of fifteen global studies (including two with national-level results for the USA and China) reported *within*-model divergences for historical material stocks. This highlights a general lack of uncertainty and sensitivity analyses for historical material stock estimates, particularly in forward-looking studies where such analyses are often lacking.

In summary, while some material stock estimates showed good to reasonable alignment (e.g., factor 1.1 for iron & steel in Chinese machinery; factor 1.04 for Viennese residential building stocks), many estimates of the same material stocks differed by multiple factors *between* studies and across all spatial scales. For example, median divergences in estimates across all stock end-uses (sum of overlapping materials) reached a factor of 2.1 at the global level, 2.4 for the USA, and 3.4 for China. This means that for over half of the stock end-uses (=divergences higher than the median), the highest and lowest estimates differ by >100 % (Eq. (2), corresponding to differences >factor 2). Divergences for specific materials within these end-uses are often much higher. In combination with the often lacking uncertainty and sensitivity analysis, these large inconsistencies in historical stock estimates pose substantial challenges for robust decision-making.

These discrepancies highlight the need for further investigation into the underlying sources of uncertainty *within* and *between* models (see Section 5), as well as the importance of identifying strategies to reduce these discrepancies, improve model consistency and to deal with uncertainty (Section 6).

5. Divergences in material stock estimates emerge from aleatory & epistemic uncertainty

Because material stocks at urban to global levels cannot be measured directly, their quantification relies on diverse data sources (Section 3). These sources vary in availability and quality, which introduces inherent uncertainty into material stock estimates (Laner et al. 2014).

In this section, we discuss sources of uncertainty *within* and *between* material stock estimates along the procedural steps in Material Flow Analysis (MFA, Table 1). To do this, we synthesized uncertainty frameworks from MFA and Life Cycle Assessment (Huijbregts 1998; Saxe et al. 2020; Brunner and Rechberger 2016; Laner et al. 2014; Laner et al. 2016).

Uncertainty *within* material stock estimates comes as *aleatory* and *epistemic* uncertainty (Huijbregts 1998; Laner et al. 2014; Laner et al. 2016; Brunner and Rechberger 2016). *Aleatory* uncertainty originates from natural variability in the 'real world' underlying the scientific problem (MFA step 1 in Table 1). An example is the variability of the material intensity of different building construction types (see Table 1, MFA step 1 for an example). *Epistemic* uncertainty originates from the uncertainty of *choices, models*, and *parameters*. Epistemic *choice* uncertainty stems from unavoidable modelling choices, which remain subjective to some degree, such as the choice of system boundaries regarding what to include and exclude (Table 1, MFA step 1). Epistemic *model* uncertainty stems from the model structure and implied variable relationships, such as stock lifetime functions applied in calculations (Table 1, MFA step 1). Epistemic *parameter* uncertainty refers to the uncertainty of model input parameters (MFA step 2), such as lack of temporally, spatially, and technologically representative data, incomplete data, inaccurate measurements, and lack of uncertainty information (Table 1, MFA step 2). Epistemic parameter uncertainty fuses with epistemic model uncertainty in MFA step 3, when data and formal mathematical model are combined via the tailoring of model data to system definition, and when proxies are used for missing values (Table 1, MFA step 3). Finally, uncertainty also simply stems from inaccurate communication and documentation, for example when ambiguous labels are used for materials or components when reporting material intensities (Table 1, MFA step 4).

A key source of uncertainty *within* material stock estimates arises from scarce and low-quality input data, which makes it difficult to adequately represent natural variability. High natural variability is, for instance, evident in recent collections of building material intensity data for specific countries (Sprecher et al. 2022; Guven et al. 2022; Lederer et al. 2021; Yang et al. 2020). So far, most such databases do not adequately represent natural variability, partly due to the time intensive process required for their compilation (e.g., Gontia et al. 2018; Fishman et al. 2024; Guven et al. 2022; Lanau et al. 2025). The lack of representative data forces modelers to make various choices, assumptions, or approximate data which can strongly influence results. Examples include the extrapolation of sampled data from individual buildings to represent the buildings material composition of entire countries; the use of country-level buildings floor space per capita as a proxy for entire world regions; and choices between different average product lifetimes (Miatto et al. 2017b; Wiedenhofer et al. 2024b; Pauliuk et al. 2021). Although relatively better data exist for bulk material flows, functional/product unit stocks, and material intensities of residential buildings, roads, and passenger vehicles, these data still face limitations. These limitations include low geographic coverage (particularly in the Global South), limited granularity in construction types and building age, and inadequate representation of geospatial variability (Table 1). Less is known about non-residential buildings and other end-uses like industrial machinery, with extremely scarce data on the age-structure and lifetimes of material stocks (Miatto et al. 2017b; Guo et al. 2021), as well as the end-use destinations of material flows (Streeck et al. 2023). Furthermore, information on the uncertainty associated with model parameters is even harder to obtain (Laner et al. 2014), which might be a reason why many studies lack uncertainty analysis.

Uncertainty *between* material stock estimates arises from the differences outlined for *within*-model uncertainty above (and summarized in Table 1) across models. These differences include variations in system boundaries when including distinct parts of a system, and the use of entirely different model structures and data sources (see Table 1 & Section 3). For instance, data sources and models may substantially differ in their estimates of functional units such as floor space (e.g., estimates from remote-sensing by Arehart et al. (2021) being factor 2–3 larger than other statistical sources). Other differences include study completeness, such as variations in indicator definitions (e.g., differences between useful, net, gross, or total built-up area, and whether unoccupied buildings are included or excluded, see Schiller et al. 2019; Arehart et al. 2021), as well as the level of data granularity, use of proxies, and inter/extrapolations (e.g., using average vs. age-cohort-based material intensities; Ortlepp et al. 2018; Lanau et al. 2019)). Additionally, a comparison of different MFA methodologies — such as *top-down* and *bottom-up* — can lead to differing estimates, for instance, due to incomplete data for either approach (Schiller et al. 2017c; Lanau et al. 2019; Grossegger et al. 2024).

The uncertainty *within* models is commonly assessed by uncertainty and sensitivity analysis – although only about half of the studies with global scope selected for this review employed such methods (see Section 4). Laner et al. (2014) outline two steps for uncertainty analysis: The first step characterizes the uncertainty of input data by uncertainty functions. This can, for instance, occur by classifying input data according to predefined uncertainty categories and assigning uncertainty functions accordingly. Given the oftentimes limited availability of data on uncertainty, this process frequently relies on expert judgement and structured, semi-quantitative procedures such as the pedigree matrix. These classifications can then be translated into (symmetric or asymmetric) probability distributions or fuzzy intervals for each parameter (Laner et al. 2015; Lupton and Allwood 2018). The second step propagates uncertainty from model inputs to outputs, which can be done either analytically or through Monte Carlo Simulations. A particularly suited (albeit labor-intensive) approach for consistently handling scarce data and attached uncertainty is Bayesian inference (Lupton and Allwood 2018). In cases where uncertainty cannot be characterized — due to a lack of data or resources for analysis — at least sensitivity analysis should be conducted to evaluate the impact of potential variations in model parameters on the results. For analysis of the uncertainty *between* models, a systematic model intercomparison would be a valuable next step towards more robust assessments.

6. Towards a more robust knowledge base on economy-wide material stocks

Robustly informing sustainable resource use strategies would benefit from more consistent, reliable, and granular evidence on economy-wide material stocks. For example, understanding the quantity and composition of materials in the housing stock, as well as the demand for floorspace at high spatial resolution, can help identify hotspots for GHG emission mitigation (Napiontek et al. 2025).

In the *short term*, this requires improved use of already available data by explicitly and transparently addressing their inherent uncertainties and sensitivities. In the *medium term*, efforts should focus on reducing uncertainty by addressing critical data gaps and promoting open access and FAIR (Findability, Accessibility, Interoperability, and Reuse) research data (Wilkinson et al. 2016; Hertwich et al. 2018). Achieving these improvements will ideally:

1) facilitate today's decision-making under uncertainty to address urgent environmental crises,
2) strengthen the robustness of estimates for *already existing* material stocks and related material and energy flows, including stock maintenance, replacement, operational energy use, and potentially available secondary resources from stock demolition,
3) improve the accuracy of assessments of *new* stock construction, which is important given the expected increase in material stocks in the future (Krausmann et al. 2020; Wenz et al. 2020; UNEP 2023a),
4) advance the modelling of cross-sectoral interactions between different material stock types, which enables the detection and avoidance of problem-shifting as a result of mitigation measures (e.g., in Integrated Assessment Models of climate change; Mastrucci et al. 2023).

These improvements will facilitate more robust, stock-flow consistent assessments of future resource use pathways and help identify the most effective stock-related mitigation strategies to reduce resource demand and related environmental impacts. For holistic resource management, stock-based indicators must be complemented with additional metrics, such as material flow indicators for purposes other than stock building, or material footprints.

In the *short term*, resource management decisions for material stocks must rely on the existing uncertain and unsystematic knowledge base. To inform mitigation efforts for pressing environmental problems with limited information, practitioners quantifying material stocks should prioritize the following:

- **Systematic uncertainty & sensitivity assessment *within* models can identify the key knowledge gaps in material stock research, and strengthen the evidence base for decision-making under uncertainty**. A major challenge in uncertainty analysis within models is the lack of information on uncertainty characterization and complex propagation (Laner et al. 2014; Brunner and Rechberger 2016). This may explain why uncertainty assessment in MFA remains an exception rather than the norm. To characterize uncertainty, studies on the variance, representativeness, and uncertainty of model input parameters are urgently needed (Table 1, Fishman et al. 2024). In the meantime, the guiding questions and uncertainty sources listed in Table 1 may assist practitioners in semi-systematically assessing and reporting uncertainty within MFAs. Additionally, conducting sensitivity analysis is crucial to identifying where data, assumptions, and uncertainties substantially impact study findings and recommendations. Furthermore, by viewing MFA as an initial evidence base that underscores the need for further analysis, follow-up studies can be designed to reduce uncertainty, particularly for local applications. For example, identifying high reuse potential in building materials within a neighborhood via MFA could prompt local planners to mandate a detailed survey of reuse potential for any building requesting a demolition permit.

- **Transparent documentation of system boundaries, methodologies, open-access workflows, and data is a precondition for reproducible assessments, the comparability of different material stock estimates, and cumulative research.** The choices made for system definitions and methods are not trivial, and large, sometimes implicit differences can exist between studies (Table 1). Developing explicit and flexible system definitions, comprehensive documentation (ideally reporting results for stock sub-components), and traceable data sources and modelling steps are desirable and a core element of cumulative research (Pauliuk 2020). Ideally, data, workflows and software should be deposited in open-access repositories to facilitate reproducibility and replicability. Helpful guidelines on systematic data compilation are available, such as those by authors from the International Society for Industrial Ecology (Pauliuk et al. 2024b) and the FAIR data initiative (Wilkinson et al. 2016).

In the *medium term*, reducing data gaps and epistemic uncertainty will require further investigation, improved measurement techniques, the integration of new data sources, refinement of modelling assumptions, and standardization (Huijbregts 1998; Brunner and Rechberger 2016). Researchers should collectively focus on the following key frontiers:

- **Systematic data pipeline and model intercomparison projects should be conducted on a regular basis to identify the reasons for disagreement between models** and to test the impact of harmonized assumptions, similar to practices in climate, energy systems, and integrated assessment modelling (Wilson et al. 2021). Currently, this is challenging due to the limited availability of studies covering overlapping temporal periods (see Section 2). In many cases, an exact temporal scope of model results cannot even be assigned, as data sources referencing different years often need to be combined (e.g., in spatially-resolved bottom-up studies).
- **Global consensus datasets on model input parameters are required to improve comparability across scales and provide standardized data and methodologies.** Currently, model input parameters are often not representative, inconsistent across scales and include various assumptions (Table 1). A key improvement would be to ensure consistency in the dimensional indicators used for stock accounting. For example, building dimensions are measured as useful, net, gross, or total built-up floor area across the literature. Similarly, road width may refer to the roadway itself, sometimes including sidewalks and auxiliary structures, or excluding them. Harmonizing these indicators towards consistency should ideally follow defined standards. While ISO 9836:2017 was previously suitable for this purpose for buildings (Schiller et al. 2019), it has been withdrawn, and the newly released international property measurement standard (IPMSC 2023) is the best available candidate (Lanau et al. 2025). Additional improvements include reconciling aggregate statistics, such as national floor area and building archetypes, with high-resolution data regarding spatial scales and construction/product type. Furthermore, a consensus on methods and open-access implementations for data processing is required. By now, initial material stock-related datasets for buildings, which synthesize data from various sources, have taken first steps in harmonization —such as harmonizing labels, reference units, and time scopes (Heeren and Fishman 2019; Röck et al. 2023; Fishman et al. 2024). However, further efforts are needed to harmonize system boundaries due to remaining inconsistencies (Heeren and Fishman 2019). Ideally, granular information from unharmonized source data should remain accessible during the harmonization process (Lanau et al. 2025). To ensure that consensus datasets do not simply obscure uncertainty by preventing further assessments, they should be continuously updated with the best available information, as is done in scenario modelling and Life Cycle Assessment.
- **Statistical agencies and researchers should establish a mutual relationship to further material stock-related knowledge.** Researchers can provide cutting-edge methodologies, expertise, and quality control for updating databases and gathering data, the latter being a key endeavor of statistical agencies. Stronger collaboration will build capacity within agencies that currently focus primarily on resource flows (Eurostat 2018; UNEP 2023b) and geological stock-flow accounting (Simoni et al. 2024). This would enable 'in-house' decision support close to policy-makers and could also provide long-term funding models for maintaining databases, as universities often lack the funding models to host them sustainably.
- **Collection of representative and granular data are necessary to reduce guess-like assumptions and aggregation errors** (see Table 1), **and enhance policy-relevance through improved coverage and detail beyond commonly assessed regions and end-uses.** This requires increased primary data collection efforts, along with improved classification systems for building stocks based on construction types, in addition to use types, in order to provide more fitting material intensities (Fishman et al. 2024). There is a particular need for more data and analysis on the Global South (Mastrucci et al. 2023), stock age structure, lifetimes, and the distribution of material stock ownership and use within the population. These are important determinants for demand-side policies, such as lifetime extension (Fontana et al., 2021). Moreover, more detailed and representative data are required for end-uses that are not widely studied, such as civil engineering, digital infrastructure, industrial machinery and appliances. These data are scarce, but collecting them would enable assessments of cross-sectoral interactions (Mastrucci et al. 2023). This effort will require new (primary) data sources and open-access policies, going against the current tendency of raising paywalls where data were openly available before (e.g., World Steel Association (2025)).
- **Leveraging digital solutions, big data, and artificial intelligence offers numerous opportunities to collect, consolidate, and communicate data.** For *new* material stocks, mandatory bills of materials (e.g., building passports (Çetin et al. 2023) and building information modelling (Akanbi et al., 2018; Volk et al., 2014)) provide valuable granular data for improving material stock knowledge. For *existing* material stocks, remote-sensing and imaging techniques, volunteered geographic information, and big data (e.g., web crawling), can be used in conjunction with machine-learning to develop and improve spatial resource cadasters (e.g., (Arehart et al. 2021; Arbabi et al. 2021; Ebrahimi et al. 2022; Milojevic-Dupont et al. 2023; Olson and Saxe 2024). Digital platforms such as digital twins (Juarez et al., 2021; Lee et al., 2023) and city information modelling offer opportunities to store, continuously update, and improve data, while also facilitating comparisons between results (Lanau et al. 2024). The communication of uncertainties should be an integral

feature of such platforms, enabling decision-makers to develop resource use strategies based on transparent and reliable data.

- **Triangulation of data sources, methodologies and results – i.e., combining different approaches to quantify a specific variable – can increase robustness and overcome limitations of single approaches.** Examples include the integration of *top-down* and *bottom-up* MFA (e.g., (Tanikawa et al. 2021; Cao et al. 2019)), using demolition data to calibrate and estimate building lifetimes (e.g., (Ianchenko et al. 2020)), employing change detection from aerial photography to assess building demolitions (e.g., (Kleemann et al. 2017b)), and comparing stock-related parameters other than material stock levels —such as material flows and age structure— between *top-down* and *bottom-up* methodologies (e.g., (Streeck 2022)).

7. Conclusions

Material stock research has advanced substantially over the past decade, highlighting the importance of understanding material stocks to support sustainable resource use strategies. We identified substantial divergences *within* and *between* current quantifications of the same material stocks, and suggested avenues towards more robust assessments. While more robust quantifications of material stocks alone do not automatically lead to sustainable resource management, they provide an improved evidence base for stock-flow consistent scenario modelling. These scenarios allow us to explore future resource use and related environmental impacts over several decades. Understanding these stock-flow dynamics—such as the availability of secondary resource flows from stock demolition—is essential for identifying the most beneficial resource use strategies and policies.

To enhance the reliability and usefulness of material stock estimates, we propose the following six steps: First, all studies should include uncertainty or, at a minimum, sensitivity analyses to support decision-making under uncertainty. Second, efforts to systematically compare data and models are needed to identify the reasons for discrepancies and develop strategies to address them. Third, to reduce uncertainties in stock estimates, researchers should aim for transparent documentation, triangulation, and the development of consensual, comprehensive databases that capture spatial, temporal, and technological variations in material stocks. Fourth, to push the research frontier, there should be a concerted effort to increase the spatiotemporal and technological resolution of material stock data, including through primary data collection and the integration of available secondary data. Fifth, advancing system-wide quantification across all end-uses and regions is essential, particularly for regions in the Global South and for stock types that have been under-researched, such as infrastructures beyond power and mobility sectors. Finally, ensuring open access and FAIR data enables cumulative research, allowing the scientific community to build on the best available evidence to design and inform sustainable resource use strategies.

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Jan Streeck: Conceptualization, Data curation, Investigation, Formal analysis, Visualization, Methodology, Writing – original draft. **André Baumgart:** Investigation, Data curation, Formal analysis, Visualization, Writing – review & editing. **Helmut Haberl:** Conceptualization, Writing – review & editing, Funding acquisition. **Fridolin Krausmann:** Conceptualization, Writing – review & editing. **Bowen Cai:** Writing – review & editing, Data curation. **Tomer Fishman:** Conceptualization, Writing – review & editing. **Maud Lanau:** Writing – review & editing. **Peter Berrill:** Data curation, Writing – review & editing. **Zhi Cao:** Writing – review & editing. **Sebastiaan Deetman:** Data curation, Writing – review & editing. **David Frantz:** Writing – review & editing. **Volker Krey:** Writing – review & editing. **Alessio Mastrucci:** Data curation, Writing – review & editing. **Alessio Miatto:** Writing – review & editing. **Stefan Pauliuk:** Data curation, Writing – review & editing. **Lola Sylvie Annie Rousseau:** Data curation, Writing – review & editing. **Shoshanna Saxe:** Writing – review & editing. **Danielle Densley Tingley:** Writing – review & editing. **Gamze Ünlü:** Writing – review & editing. **Dominik Wiedenhofer:** Conceptualization, Data curation, Resources, Writing – review & editing, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2025.108324.

Data availability

All data used provided in data supplementary.

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