Building material stock analysis is critical for effective circular economy strategies: a comprehensive review

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Abstract
Buildings account for the largest share of accumulated materials and waste globally. Tracking the material composition, quantity and location of these materials, known as building material stock analysis (MSA), is a first step in enabling the reuse or repurposing of materials, key strategies of the circular economy. While the number of building MSAs is growing, there is a need to coalesce methods, data and scope. Therefore, in this work, we reviewed and evaluated 62 journal and conference articles on MSA of buildings from different angles including scope, boundaries, archetype classification, material intensity determination, approaches (i.e. bottom-up, top-down, remote sensing) and quantity of materials to identify barriers, gaps and opportunities in this area along with its implications for decision-making, policy and regulations. We cataloged the three major approaches of MSAs and discuss their advantages and shortcomings. We also created a comprehensive directory of building archetypes, references and materials for future researchers. As expected, most of the studies estimated that concrete had the largest mass compared with other materials; however, mass-based distribution of materials showed significant variations in different building stocks across the world. Also, embedded plastics and their types remain under-represented in current studies. A major barrier to MSA is related to a lack of information on physical attributes and geographic information system, design and construction data. Policy makers can play a role in mitigating data barriers through instituting regulations that enforce the reporting of building-related data during the permitting process. Furthermore, outcomes of building MSA can help policy makers when considering incentives for design and construction that utilize these abundant building materials.

1. Introduction

Global material use is projected to increase from 89 Gt to 167 Gt between 2017 and 2060, along with the associated environmental impacts, including carbon emissions from material production [1]. This projected increase in material use is due in part to the building sector that is needed to house and support our growing population [2]. The building sector in urban areas is responsible for the largest share of consumption of raw materials for producing construction materials and of accumulated materials as well as significant amounts of waste generated during construction and demolition [2–5]. In 2018, construction and demolition activities in the United States resulted in 600 Mt of waste, more than double the amount of generated municipal solid waste [6]. In the light of climate change, resource depletion and waste generation, there is an urgent need to develop and implement innovative strategies.
Replacing the current linear economic system (i.e. a take, make and waste economy) with a circular economic system has been suggested as a solution for climate change, resource depletion and waste management, with a focus on plastic pollution [7]. Circular economy strategies such as reuse, recovery, design for disassembly and extending lifetimes are intended to retain the primary value of materials and products, close the material loop, reduce natural resource extraction, reduce waste and mitigate the environmental impacts of buildings. However, the practical implementation of circular economy strategies for the building and construction sector can be difficult. While some have proposed utilizing buildings as urban mines and secondary resources, extensive knowledge and information about building stocks are first needed to realize this potential. Simply put, one cannot mine without knowledge of where the material is located, along with the type, quantity, quality and value of the material [8]. Information about buildings in several countries including the United States is usually disparate, sparse and granular [9–11].

To overcome the data challenge and compile the information about accumulated materials in existing buildings, material stock analysis (MSA) and material flow analysis (MFA) can be employed. MSA and MFA explore material dynamics and metabolism at different temporal and spatial scales and are known as support tools to foster circularity. In the last 20 years, analyzing the stock of built environments (i.e. buildings, roads, railroads, bridges, water and sewer pipe lines, and other civil infrastructure [12]) has gained attention, and several researchers have proposed different methods at neighborhood, city and country scale to understand metabolisms and estimate the quantity of available materials in these structures. Augiseau and Barles [13] summarized proposed methods and findings from 31 publications between 1998 and 2015 that analyzed the stock and flow of non-metallic minerals in the built environment, including road and railroad networks. They found that in many case studies recycling, reusing or recovering current materials in the built environment may not meet the growing demand for buildings and infrastructure. For instance, using recycled construction waste as a secondary material would decrease the need for new materials by only 7% in Vienna, Austria. In another article, Lanau et al [14] depicted a broad picture of the scope and approaches in 249 technical reports and articles covering both buildings and infrastructure that were published prior to 2018. They found that cities and urban areas are responsible for the highest share of materials in the built environment and material accumulation in developed countries is generally higher than in developing countries. Göswein et al classified methods, tools and data from studies that investigated building materials, embodied energy and emissions at the neighborhood or district level [15].

In this article we build on previous efforts while filling in the gaps from previous papers [13–15]. This work focuses on the MSA of buildings, because buildings are highly diverse and have complex systems and therefore warrant close attention to factors that may be overlooked when the entire built environment is aggregated. Unlike former review papers that narrowed their scope to specific materials [13], all types of metallic and non-metallic materials are included in this review. Moreover, this work covers the latest studies up to 2021. The spatial scale is expanded to encompass studies at the neighborhood, district, city and country levels, referred to throughout this paper as ‘at scale’.

Circular economy strategies include the reuse and recovery of materials and components. We aim to advance the circularity of the building sector by analyzing the current body of literature with a focus on the MSA of buildings, and illustrate a new and updated paradigm in this area by accomplishing the following goals:

- Characterizing the scope, system boundary and resolution of existing studies.
- Exploring and classifying the approaches for quantifying and spatializing building materials, along with the gaps and limitations.
- Compiling an inventory that contains the composition and quantity of materials in existing buildings in different parts of the world by extracting results from several studies.
- Discussing technological and data barriers and remaining gaps as well as opportunities to improve this emerging field.

2. Review method

To achieve the research goals, the narrative review method was adopted. First, Scopus, a citation database developed by Elsevier, was used to search for publications that were published after 2000 and contained ‘building material stock’, ‘building material flow’ or ‘building stock assessment’ terms in the title, abstract, or keywords with an emphasis on peer-reviewed journal and conference publications. More than 11 000 publications were found in the Scopus database under the aforementioned criteria; however, several irrelevant articles were included. We reviewed the abstracts of all publications through a rigorous process and identified 62 articles that were directly related to the focus of building MSA at scale and were published between 2001 and February
The 62 articles comprised 59 research articles, which investigated the accumulated materials in different building stocks across the world, and three review articles.

For reference, building stock is the total number of existing buildings with distinct material and operation characteristics in a region. The analysis of accumulated materials in a building stock has several aspects. One aspect is the parameters that represent scopes and boundaries including function or use type, components of buildings, spatial boundary and temporal resolution. The 59 research articles were critically reviewed for scopes and boundaries in section 4. A building stock is also classified into groups of buildings with similar material characteristics, known as archetypes. In section 5, a thorough discussion on archetypes, material intensity, and various data sources used for determining the material intensity is provided. One of the key aspects of developing a MSA is the approach. Building MSAs and their practical application for fostering circularity are tied to the approach. Thus, in section 6, different approaches are assessed concerning data acquisition, advantages, and shortcomings. Ultimately, the results including materials and composition are critically reviewed in section 7.

3. Progress in material stock analysis of buildings

The chronological trend of publication dates is displayed in figure 1. This increasing trend can be attributed to recent interest in the circular economy, urban mining, resource reuse, innovations in geographic information systems (GISs), aerial photogrammetry and building disclosure policies (e.g. the State of California mandated buildings over 50 000 ft² to disclose basic building information such as floor area as well as energy use data). As the area of building MSA evolves over time, the inclination to employ bottom-up approaches has risen (see figure 1). In addition to the number of publications over time, the level of detail has improved; for example, more types of material have been accounted for in recent publications.

Of the 62 reviewed articles, 59 were research articles. We investigated the type and number of materials, that were included in these research articles, in accordance with their year of publication. As shown in figure 2, in recent years researchers have been conducting more in-depth and comprehensive analyses of buildings by incorporating more types of building material in the stock analysis than in the early 2000s. Out of 27 studies published from 2018 to 2021 and 20 studies published from 2014 to 2017, 23 (85%) and 15 (75%) studies estimated the quantity or calculated the material intensity of more than one type of building material, respectively. However, this percentage was lower for studies published in the early 2000s (see figure 2). Two studies proposed frameworks for MSA without quantifying or spatializing building materials [16, 17], Turan and Fernández [16] and Lismont and Allacker [17] elaborated on classifying buildings into representative buildings or archetypes using manual and k-means clustering algorithms, respectively. Three articles reported the total accumulated
building materials in different cities and countries without providing more disaggregated results regarding the types of materials [18–20]. This investigation shows that higher resolution and more holistic building stock assessments have been growing over time.

4. Material stock analysis scopes and boundaries

The distribution of stocks of building materials at scale is influenced by the scopes and system boundaries of studies. Thus, imperative to understanding the in-use or accumulated material stocks of buildings is characterizing scopes and system boundaries. Scopes and system boundaries can be categorized into four groups: (1) building function or use type, (2) building components, (3) spatial or geographic boundary, (4) temporal resolution.

4.1. Building function or use type

As required by the majority of codes and standards, the architectural, structural and energy designs of buildings are determined based on their function. As a result, the composition and the amounts of materials are affected by the building function. The functional system boundaries of reviewed articles mostly contained residential buildings (42%) or a combination of residential and non-residential buildings (52%); few articles limited their scope to solely non-residential buildings [21, 22]. Although there was not a definite explanation for the lower numbers of non-residential buildings, some factors were probably related to the complexity and diversity of construction techniques and structural systems. There is need for an emphasis on non-residential buildings especially because they have a shorter average life span than residential buildings, which increases the frequency of demolition and consequentially the availability of reusable and recoverable materials [23].

While a consensus has been formed on categorizing building function into two broad categories (residential and non-residential), there has been less agreement about how to categorize building stock into different functional subcategories (e.g. non-residential municipal). There are overlaps and similarities between several functional subcategories both for residential and non-residential buildings, but distinct or disparate language was utilized in different articles; for example, institutional buildings may have similar functions to economic or education buildings. We identified nine residential and 19 non-residential building subcategories (see table 1).

In several studies, residential buildings were clustered into single-family and multi-family, based on the number of units. A few studies considered the adjacency of buildings (detached house, semi-detached house and townhouse) [17, 24–28]. An important parameter is building height, which influences the quantity and composition of materials and consequently affects the spatial distribution of accumulated materials in a region [22, 29]. For non-residential buildings, height was inherently considered in some of the subcategories; for example, institutional, retail and warehouse buildings were usually considered as a single story, and office buildings were usually designed with multiple stories [22]. Despite the importance of height, it has rarely been incorporated in defining residential subcategories and only a small number of studies acknowledged the difference between high-rise and low-rise residential buildings [25, 26, 28, 30]. As illustrated in table 1, there is a notable disparity among different articles regarding the language or terminologies utilized to describe functional subcategories. This disparity is a barrier to the reproducibility of building MSA.
Table 1. Building function categories and subcategories for some of the reviewed articles. Note: factory, government, storage, and school and childcare facility are included as industrial, institutional, warehouse and education subcategories, respectively.

| Reference | Author(s) Year | Residential | Non-residential |
|-----------|----------------|-------------|-----------------|
| [24]      | Mellaci et al (2021) | ![Residential Category] | ![Non-residential Category] |
| [25]      | Ajayebi et al (2020)   | ![Residential Category] | ![Non-residential Category] |
| [32]      | Bradshaw et al (2020)  | ![Residential Category] | ![Non-residential Category] |
| [33]      | Yang et al (2020)      | ![Residential Category] | ![Non-residential Category] |
| [34]      | Mao et al (2020)       | ![Residential Category] | ![Non-residential Category] |
| [35]      | Gao et al (2020)       | ![Residential Category] | ![Non-residential Category] |
| [36]      | Gontia et al (2020)    | ![Residential Category] | ![Non-residential Category] |
| [26]      | Deere et al (2020)     | ![Residential Category] | ![Non-residential Category] |
| [37]      | Gontia et al (2019)    | ![Residential Category] | ![Non-residential Category] |
| [4]       | Stephan and Athanassiadis (2018) | ![Residential Category] | ![Non-residential Category] |
| [22]      | Schlebek et al (2017)  | ![Residential Category] | ![Non-residential Category] |
research. To overcome this barrier, collective terminologies such as the International Standard on Building and Civil Engineering Works Vocabulary can be employed to define functional subcategories [31]. In addition, the use of unified and coherent terminology enables businesses and companies to adopt the results of academic research for adaptive reuse (repurposing) of buildings based on their function. The building function categories and subcategories for all reviewed articles are provided in the supplementary materials (https://stacks.iop.org/ERIS/2/032001/mmedia).

4.2. Building components

Building materials are found in structural components (e.g. roof and floor elements, columns, beams, wall panels) and non-structural components (e.g. roof and wall insulation, windows, non-bearing partitions, interior finishes, mechanical, electrical and plumbing (MEP) elements [38]). The obsolescence or recovery paths of structural components are different from those of non-structural components. The former, which are chiefly made from masonry, wood, concrete and steel, usually become available at the end of a building’s lifetime [27, 39]. Although there is a growing interest among building professionals in industry and academia in the reuse of structural components and returning them to a service loop while preserving initial value, considerable shares are still recycled or discarded in landfill. Recycling of these components is either energy-intensive (e.g. steel) or associated with significant downgrading (e.g. crushing concrete into aggregate for further use in recycled concrete and pavement). The challenge of reuse is linked to a lack of building standards and regulations for testing the integrity of the structural components used, the complexity of transforming traditional structural design in a way that can incorporate mechanical and geometric properties of reclaimed components into the design process and a lack of enterprises that can bridge the gap between deconstruction and new construction [40, 41]. On the other hand, non-structural components are easier to access, sort and handle upon deconstruction, which facilitates reuse. Further, these components such as MEP elements and windows are more frequently replaced during a building’s lifetime due to weather and utilization stresses, which make their adaptive reuse economically and environmentally beneficial [42]. The different obsolescence characteristics of structural and non-structural components point to the need to specify scope with respect to the type of component beyond summing up the volume or mass of materials when conducting MSA [43].

To this point, 80% of reviewed studies analyzed materials accumulated in both structural and non-structural components without differentiating between the two component categories. Few articles (19% of reviewed studies) constrained their system boundaries to structural components [25, 30, 34, 44–50], whereas only Stephan and Athanassiadis [4, 51] quantified and spatialized materials in non-structural components (i.e. floors, external walls, internal walls, windows, doors, roofs, pipes, wires) of Melbourne’s building stock. This evaluation reveals that future MSAs need to consider and distinguish between materials available from different components to enable appropriate planning for circular usage in alignment with the respective lifetimes.

4.3. Spatial boundary

The total quantity of accumulated materials within a region and the level of detail about the exact location of materials are affected by the spatial boundary of a study. We have identified six spatial boundaries (i.e. global, continent, country, city, district, neighborhood) in the current body of work. Deetman et al [26] and Marinova et al [27] developed global building materials models by using population and floor area per capita data and reported total accumulated building materials in the world. In one study, Wiedenhofer et al [30] conducted a continent-scale MSA and estimated concrete and minerals in residential buildings of 25 countries that formed the European Union at the time of the study. Twenty-four articles analyzed the material stock of buildings for 14 countries located in Asia, Europe and North America. The highest frequency of country-scale studies came from Germany (five studies [21, 46, 52–54]), China (five studies [33, 55–58]) and Japan (four studies [18, 57, 59, 60]) followed by Sweden (two studies [36, 61]), Norway (two studies [28, 62]) and Switzerland (two studies [63, 64]). Twenty-four articles quantified or spatialized building materials of 34 cities across the world. The inconsistency between the number of articles and the number of cities was because few articles explored more than one city [24, 25, 45, 65]. For example, Guo et al [45] and Surahtman et al [65] calculated the quantity of materials in buildings in 14 cities in China and two cities in Indonesia, respectively. Likewise, Mollaei et al [24] estimated the building materials of Kitchener and Waterloo in Canada, and Ajayebi et al [25] developed a model to draw the spatial distribution of bricks in building stocks of Manchester, Bradford and Leeds in the United Kingdom. Among city-scale research articles, Beijing and Shanghai in China and Vienna, Austria have been investigated by multiple studies. Finally, five and three articles limited their geographic scopes to districts [3, 19, 43, 66, 67] and neighborhoods [16, 44, 68], accordingly.

The high variation in the spatial boundary of studies increases the difficulty of comparing and validating results. This variation also complicates the transferability of data and outcomes between different regions. A closer look at geographic location showed that the majority of studies (80%) were concentrated in European countries, Japan and China, while 8% were conducted in North America, and the remaining studies (12%)
Figure 3. Number of articles from different countries with various spatial boundaries. Note: few articles analyzed building material stocks in more than one country.

were located in Australia, Asia and South America or covered the entire world (see figure 3). Unfortunately, no studies were found in Africa. Note that a country-scale study by Fishman et al [59], which included both the United States and Japan, is considered in Japanese and North American percentages. Figure 3 displays the number of articles in different countries that conducted building MSAs regardless of spatial boundaries. For example, as shown in figure 3, three articles analyzed material stocks of buildings in the United States [59, 66, 69]; however, the spatial boundary of these articles varied. Fishman et al [59], Reyna and Chester [69] and Marcellus-Zamora et al [66] analyzed material stocks of the entire United States (country scale), Los Angeles (city scale), and University City in Philadelphia (district scale), respectively.

4.4. Temporal resolution

While building stocks are inherently dynamic in relation to time due to variations in demand for new buildings, recurrent renovations and maintenance during a building’s lifetime, and demolition at the end of life, materials have been analyzed both statically and dynamically. The temporal resolution affects the selected approach and outcomes of MSA, which is thoroughly discussed in section 6. In a static MSA, a time interval (e.g. 1 year) is selected and building material stock is represented for the chosen interval. Although the static approach does not provide insight into the trend of material accumulation over time, it does not suffer from the uncertainty associated with the inaccuracy of historical data or future projections. Several studies (32% of reviewed articles) utilized the static approach to estimate material stocks [3, 16, 17, 21, 22, 25, 32, 34, 45, 53, 64, 70, 71].

The dynamic approach accounts for the change in stocks throughout time and can be classified into retrospective and prospective studies [13, 14]. Retrospective studies (34% of reviewed articles) employed either available maps or historical data to characterize building stocks from past to present. Few retrospective studies analyzed building stocks by reconstructing GIS maps based on old sketches, paper maps, aerial images and digital maps [19, 20, 43, 67]. On the other hand, several studies relied on historical data (e.g. population, floor area) [10, 18, 29, 36, 37, 49, 55, 59, 66, 69, 72–75]. Prospective studies (8% of reviewed articles) predicted and characterized building stocks in the future [4, 24, 51, 63, 68, 76]. In addition to these dynamic approaches, retro-prospective studies investigated the building material’s metabolism from the past to future [26–28, 30, 35, 44, 48, 50, 60, 65]. The temporal span of dynamic MSA ranged from a few years to centuries. In one example, Marcellus-Zamora et al [66] developed and validated a dynamic model to understand the material stock and flows of a neighborhood over 8 years. However, Müller [50] assessed input flows, in-stock and output wastes of concrete in the housing stock of the Netherlands between 1900 and 2100 by defining different scenarios.

5. Building archetype and material intensity

Diversity in the composition and intensity of materials among buildings is noticeable because of heterogeneity in design and availability of materials in different parts of the world and during various time periods. Nonetheless, obtaining and employing detailed data about materials for every individual building at scale is relatively difficult or not likely to be feasible. To overcome this challenge, the common practice is to define archetypes or typologies that represent groups of buildings with similar characteristics regarding materials. To classify a building stock into archetypes, the time of construction was prevalently utilized in the reviewed articles (see
In addition, we identified other categories for archetype classification, including building function, structure type, renovation state, urban versus rural, building height, floor count, construction cost and lot size, and climate zone. As displayed in Table 2, the number of archetypes varied significantly. Classifying a building stock into more archetypes allows for capturing and integrating the diversity of buildings to a higher degree, which enhances accuracy. In addition to archetype classification, determination of material intensity is an important factor.

Material intensity is one of the key parameters in MSA and indicates the amount of a certain material per unit of a building such as mass per floor area, mass per building, mass per volume of a building, volume per building and volume per volume of a building. More definite determination of material intensity for archetypes increases the accuracy of results and mitigates uncertainty. As shown in Table 2, several studies relied on previous literature as well as building standards, handbooks and manuals for material intensity. The drawback of dependence on previous literature is that it may cause uncertainty propagation. Identifying and investigating sample buildings that were representative of archetypes through construction documents, life cycle assessment (LCA) inventories and on-site inspection were other methods used to determine material intensity. Moreover, data embedded in building information models (BIMs) can be retrieved and employed to estimate the material intensity of sample buildings [16]. One-third of the articles in Table 2 evaluated sample buildings; however, straightforward procedures for on-site inspection and extracting material information from construction documents of old buildings were not described in these articles.

Advances in determining the material intensity of building stocks require systematic collection and documentation of design and construction data to create comprehensive and publicly available inventories. Instituting policies and regulations that instruct design firms and construction companies to report the composition and quantity of materials in a building will help the creation of such inventories. In addition, leveraging technologies such as BIM will not only facilitate documenting materials but also enable consideration of materials like plastics that are currently less considered in building MSA. Table 2 summarizes the categories that were utilized for classifying archetypes, the number of archetypes and how material intensity was determined as well as the units of material intensity. This table can be adopted for assessing the transferability of material intensity in different regions as well as employing material intensities in existing articles for future research.

6. Approaches

A detailed review of articles revealed different approaches for developing MSA. As displayed in Figure 4, the approaches can be clustered into bottom-up, top-down and remote sensing. While selecting an approach to conduct MSA depends on the objectives of a study as well as available data and tools, it has an impact on how the results of MSA can be utilized to redirect entire or some fractions of materials to a resource loop. Therefore, it is important to summarize and critically assess the advantages and shortcomings of these approaches, especially from the lens of the circular economy. Figure 4 demonstrates a basic sketch for the modeling structure of different MSA approaches. The directions of the arrows indicate the steps for developing a MSA model that starts from acquiring input parameters or variables and ends with meshing the parameters with material intensity.

6.1. Bottom-up approaches

Primarily, bottom-up approaches are used to quantify and geolocate materials by combining physical attributes of buildings (i.e. floor area, volume, surface area) with materials intensity. These approaches provide the opportunity to produce finer results (usually at the building level) than other approaches. While the development of bottom-up models is data intensive and laborious, recent progress in GIS with increased data transparency and mandates in cities and municipalities has facilitated the creation of these models. To obtain the physical attributes of buildings, distinct methods have been proposed and tested. These methods are critically reviewed in the rest of this sub-section.

Floor area from existing inventories. Some cities and countries have inventories containing either the floor area of individual buildings [10, 35, 60, 68, 76, 111], coded based on a variety of identification (ID) tools such as property tax ID, or average floor area for different archetypes [36, 49, 53, 69]. Lausselet et al [68] used the individual building floor area of a neighborhood under development in combination with material intensity and quantified metallic and non-metallic materials. Similarly, Cheng et al [111] and Condexia et al [76] derived the floor area of every building from the Taipei City Construction Management Office and Rio de Janeiro Construction License databases, respectively, to estimate accumulated materials at the city scale. Hashimoto et al [60] obtained the floor area of individual buildings from the fixed asset prices report and utilized it in conjunction with materials intensity to estimate the total materials embedded in the Japanese building stock. Gontia et al [36] derived both the average usable floor area for every archetype and the number of buildings under different archetypes from national databases. By multiplying the usable floor area and the corresponding number
Table 2. Summary of archetype classification, material intensity determination, and material intensity units in the reviewed articles.

| Reference | Author/s (year) | Time of construction | Other categories | Material intensity for archetypes |
|-----------|----------------|----------------------|------------------|-----------------------------------|
|          |                |                      |                  | Determination methods/resources   | Unit                        |
| [24]     | Mollaei et al (2021) | Before 1930 1930–1960 1961–1975 | 1976–1999 | Existing literature [61, 69, 77–79] | kg m\(^{-2}\) |
| [25]     | Ajayebi et al (2020) | Before 1850 1851–1945 1946–1970 After 1971 | 2000–2018 | Expert opinion | |
| [32]     | Bradshaw et al (2020) | — | Building function | Evaluation of 303 sample buildings via on-site inspections | No. of bricks m\(^{-2}\) |
| [33]     | Yang et al (2020) | 1949–1959 1960–1979 1980–1989 | 1990–1999 | Evaluation of 813 sample buildings via existing literature | t (100 m\(^2\))\(^{-1}\) |
| [34]     | Mao et al (2020) | Before 1980 1981–2000 2001–2018 | Building function | Evaluation of 1800 sample buildings via construction documents, existing literature, and expert opinion | kg m\(^{-2}\) |
| [35]     | Gao et al (2020) | Before 1949 1950–1959 1950–1979 1950–2010 1950–2100 1960–1979 After 2000 | 1965–1979 1980–1989 1980–1999 1990–1999 1990–1999 | Building standard, handbook, manual | kg m\(^{-2}\) |

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| Reference | Author/s (year) | Time of construction | Other categories | Determination methods/resources | Material intensity for archetypes |
|-----------|----------------|----------------------|-----------------|--------------------------------|----------------------------------|
| [36]      | Gontia et al (2020) | Before 1930, 1931–1950, 1951–1980, After 1981 | Building function | Existing literature [61] | kg m\(^{-2}\) |
| [68]      | Lausselet et al (2020) | 2019–2020, 2021–2025, 2026–2030, 2031–2080 | Building function, Renovation state | Construction documents | kg m\(^{-2}\) |
| [72]      | Lederer et al (2020) | Before 1919, 1919–1945, 1946–1980, 1981–2000 | Building function | Evaluation of 66 sample buildings via construction documents, LCA inventory, on-site inspection | kg m\(^{-2}\) |
| [3]       | Romero Perez de Tudela et al (2020) | Before 1919, 1919–1939, 1945–1964, 1965–1983, 1984–1992 | Building function | Evaluation of 12 043 sample buildings via existing literature [83] | kg m\(^{-2}\) |
| [43]      | Guo et al (2020) | Before 1950, 1960–1979, 1980–1989, 1990–1999, After 2000 | Building function, Structure type (brick–concrete, brick–wood, reinforced concrete) | Existing literature [33, 82] | kg m\(^{-2}\) |

(continued on next page)
| Reference | Author/s (year)          | Time of construction | Other categories | Material intensity for archetypes |
|-----------|-------------------------|----------------------|------------------|----------------------------------|
| [26]      | Deetman et al (2020)    | —                    | Building function | Urban vs rural                    |
|           |                         |                      | 12               | Existing literature               |
| [70]      | Tazi et al (2020)       | Before 1919          | Building function | Structure type                    |
|           |                         | 1919–1945            | 1971–1990        | (brick, concrete, stone, wood)   |
|           |                         | 1946–1970            | 2006–2013        | kg m⁻²                           |
| [27]      | Marinova et al (2020)   | —                    | Building function |                                 |
|           |                         |                      | 4                | Existing literature               |
| [37]      | Gontia et al (2019)     | Before 1920          | Building function |                                 |
|           |                         | 1921–1950            | Before 1930      | Evaluation of 15 sample buildings |
|           |                         | 1951–1980            | 1931–1980        | via construction documents       |
|           |                         | After 1981           | After 1981ᵇ      | Existing literature [61]          |
| [44]      | Wang et al (2019)       | —                    | Structure type   |                                 |
|           |                         |                      | (brick–concrete, |                                 |
|           |                         |                      | steel)           | Existing literature [84–86]       |
| [45]      | Guo et al (2019)        | —                    | Structure type   |                                 |
|           |                         |                      | (brick–concrete, |                                 |
|           |                         |                      | reinforced concrete) | Existing literature [81] |
| [10]      | Arora et al (2019)      | —                    | Building function |                                 |
|           |                         |                      | 1                | Evaluation of five sample buildings |
|           |                         |                      |                  | via construction documents       |
| [73]      | Miatto et al (2019)     | Before 1902          | Building function |                                 |
|           |                         | 1903–1954            | 1970–1981        | Building standard, handbook, manual |
|           |                         | 1955–1969            | 1982–1996        | Existing literature               |
|           |                         |                      | 1997–2007        | kg m⁻²                           |

(continued on next page)
| Reference | Author/s (year) | Time of construction | No. | Determination methods/resources | Material intensity for archetypes |
|-----------|----------------|----------------------|-----|---------------------------------|----------------------------------|
| [63]      | Heeren and Hellweg (2019) | NS | NS | NS | Existing literature [87] kg m$^{-3}$ |
| [74]      | Mesta *et al* (2019) | — | | | Evaluation of 120 sample buildings via building standard, construction documents, expert opinion, on-site inspection kg m$^{-2}$ |
| [75]      | Han *et al* (2018) | Before 1960, 1960–1980, 1980–2000, 2000–2010 | | 8 | Existing literature [58, 82, 88] kg m$^{-2}$ |
| [61]      | Gontia *et al* (2018) | 1880–1890, 1880–1900, 1890–1900, 1890–1910, 1900–1910, 1910–1920, 1920–1930, 1930–1940, 1930–1950, 1940–1950 | | 46 | Evaluation of 46 sample buildings via construction documents kg m$^{-2}$ |
| [4]       | Stephan and Athanassiadis (2018) | Before 1900, 1900–1960, 1960–1980, 1980–2000, 2001–2006, 2006–2015 | | 48 | Existing literature [89, 90] kg/ no. of components |

(continued on next page)
Table 2. Continued

| Reference         | Author/s (year)                  | Archetype classification                                                                                                                                 | Determination methods/resources            | Unit  |
|-------------------|---------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------|-------|
| [111]             | Cheng et al (2018)              | —                                                                                                                                                    | Existing literature [91, 92]               | kg m^{-2} |
| [46]              | Schiller et al (2017)           | Before 1918 1919–1948 1949–1968 After 1990 Building function                                                                                     | Existing literature [93, 94]               | t/building |
| [76]              | Condeixa et al (2017)           | —                                                                                                                                                    | Existing literatureg                       | kg m^{-2} |
| [29]              | Kleemann et al (2017)           | Before 1918 1919–1945 1946–1976 1977–1996 After 1997 Building function                                                                          | Evaluation of 66 sample buildings via construction documents, LCA inventory, on-site inspection | kg m^{-1} |
| [51]              | Stephan and Athanassiadis (2017)| Before 1900 1901–1960 1961–1970 1961–2015 1971–1980 1981–2006 Building function Building height (≤10 m, >10 m and ≤18 m, ≥19 m) | Existing literature [89, 90]               | kg/ no. of components |
| [22]              | Schebek et al (2017)            | Before 1918 1919–1948 1949–1957 1958–1968 1969–1978 1979–1994 1993–2001 Building function                                                         | Evaluation of 19 sample buildings via construction documents, on-site inspection | kg m^{-1} |

(continued on next page)
| Reference | Author/s (year) | Time of construction | Other categories | Determination methods/resources | Material intensity for archetypes |
|-----------|----------------|----------------------|-----------------|---------------------------------|--------------------------------|
| [71]      | Mastrucci et al (2017) | Before 1949 1949–1968 1969–1994 After 1994 | Building function | Building standard, handbook, manual Existing literature [95, 96] Expert opinion | kg m$^{-2c}$ |
| [65]      | Surahman et al (2017) | — | Construction cost and lot size | 3 On-site inspection | kg m$^{-3}$ |
| [52]      | Schiller et al (2017) | — | Building function | 2 NS | NS |
| [47]      | Kalcher et al (2017) | Before 1919 1919–1944 1945–1960 1961–1970 1971–1980 1981–1990 1991–2000 2000–2010 | Building function | 8 Existing literature [97–99] Evaluation of 252 sample buildings via existing literature [100, 101] | m$^3$ m$^{-2c}$ |
| [21]      | Ortlepp et al (2016) | — | Building function | 7 Evaluation of 36 sample buildings via construction documents | t m$^{-2}$ |
| [53]      | Ortlepp et al (2018) | Before 1918 1919–1948 1949–1978 After 1991 | — | 5 Existing literature Evaluation of 36 sample buildings via construction documents | t m$^{-2}$ |
| [66]      | Marcellius-Zamora et al (2016) | — | Building function | 6 Expert opinion | kg m$^{-2}$ |
| [30]      | Wiedenhofer et al (2015) | — | Building function Structure and envelope type Climate zone | 72 Existing literature [95, 102] | Mt/building |

(continued on next page)
| Reference | Author/s (year) | Archetype classification | Time of construction | Other categories | Determination methods/resources | Material intensity for archetypes |
|-----------|----------------|--------------------------|----------------------|-----------------|--------------------------------|--------------------------------|
| [19]      | Sugimoto et al (2015) | Structure type (reinforced concrete, steel, wood) | 1959 1971 1974 | 1981 2000 | 20 Existing literature [103] | kg m⁻² |
| [18]      | Tanikawa et al (2015) | Structure type (reinforced concrete, steel, steel–reinforced concrete, wood, other) | 5 | Existing literature [104] | kg m⁻² |
| [16]      | Turan and Fernández (2015) | — | — | 6 Evaluation of sample buildings via building information model | kg m⁻² |
| [69]      | Reyna and Chester (2015) | Building function | Before 1950 1950–1990 After 1990 | 42 Existing literature [79, 105, 106] | NS |
| [77]      | Ergun and Gorgolewski (2015) | Evaluation of sample buildings via construction documents | Before 1930 1931–1960 1961–1975 1976–2000 After 2001 | 5 | m²/building |
| [55]      | Han and Xiang (2013) | Structure type (brick–concrete, concrete, shearing force) | 1980s 2000s | Urban vs rural | 4 Existing literature [58, 107, 108] | kg m⁻² |
| [48]      | Hu et al (2010) | — | 3 Existing literature [108] | kg m⁻² |
| [49]      | Hu et al (2010) | Structure type (brick–concrete, steel-concrete) | 2 | Evaluation of sample buildings via construction documents | t (100 m²)⁻¹ |

(continued on next page)
**Table 2. Continued**

| Reference | Author/s (year) | Time of construction | Other categories | Material intensity for archetypes |
|-----------|----------------|----------------------|-----------------|----------------------------------|
| —         | —              | —                    | Building function Structure type (brick, reinforced concrete) | 3 | Existing literature [109] kg m\(^{-2}\) | Unit |
| [67]      | Tanikawa and Hashimoto (2009) | — | — | — | 4 | Building standard, handbook, manual kg m\(^{-2}\) |
| —         | —              | —                    | Building function Structure type (reinforced concrete, steel, wood) | 16 | Evaluation of 11 sample buildings via construction documents, on-site inspection t/building |
| 1900–1925 | —              | 1901–1920            | — | 1926–1950 | 1951–1975 | 1976–2000 | 1941–1945 | Building function | 45 | Expert opinion kg m\(^{-2}\) |
| —         | —              | —                    | — | — | — | — | — | — | Amount of produced material per floor area t m\(^{-2}\) |

\*Not all categories exist in every time period.  
\*Three time periods for non-residential buildings and four time periods for residential buildings.  
\*Material intensities were determined for every component (e.g. roof) of every archetype.  
\*Material intensity (no. of bricks m\(^{-2}\)) represents the number of bricks per unit area of an external wall.  
\*Material intensity (m\(^3\) m\(^{-3}\)) represents the volume of timber in m\(^3\) per gross volume of a building.  
\*Number of sample buildings was not specified.  
\*Books, databases, journal articles or reports, which were used as existing literature, were not specified.  
\*Several books, databases, journal articles or reports were used as existing literature. Refer to the article.  
\*LCA and NS refer to life cycle assessment and not specified, respectively.
of buildings, the total floor area and further material stock of Sweden’s residential buildings were calculated [36]. Using average floor area per archetype inhibits geolocating or mapping materials at building-level which is important for efficiently recirculating materials to a consumption loop through different means (e.g. reuse, recycle, repurpose). Also, it causes over- or under-estimation of floor area, which exacerbates uncertainty of estimated materials.

Besides data about floor area, there are inventories or databases that contain the number of buildings. Wiedenhofer et al [30] and Lichtensteiger and Baccini [64] extracted the number of buildings per archetype from available databases in the European Union and Switzerland, respectively. The former compiled the data from multiple sources (i.e. Eurostat, European Housing Statistics reports and national databases of different European countries) and the latter obtained the data from a previous study [112]. In both studies, the number of buildings per archetype was multiplied by materials intensity in the form of mass per building of the corresponding archetype to estimate accumulated materials. Although incorporating the number of buildings per archetype resolved miscalculation due to using the average floor area of every archetype, in [30] floor area and in [64] floor area and structure type were not included for classifying archetypes and determining the material intensity, respectively (see table 2). Thus, materials intensity in both studies did not reflect the influence of the diversity of building size or structure type on materials quantity and composition.

Floor area from GIS analysis. As displayed in figure 4, floor area per story has been commonly employed in bottom-up models. This parameter is defined as the area of a representative polygon of a building and is obtainable from GIS databases. Utilizing the areas of polygons can provide two advantages. First, information about materials (i.e. amount and composition) can be geolocated at a building level. The geolocation at this fine scale allows local businesses and companies to plan for less destructive demolition and handling, sorting, storing and trade of components and materials. Second, GIS-based software platforms such as ArcMap offer drawing and geometric calculation tools. These tools enable the refinement of the representative polygons to match the real-world shape of buildings and a more accurate estimation of the polygon areas of the buildings.

Several studies obtained the floor area of every building in studied regions by multiplying floor area per story by floor counts (number of stories in a building), which were both available via GIS data for cities and countries [18, 24, 34, 44, 45, 67, 75]. For China, this method was adopted for many cities (e.g. Beijing, Shanghai) and the estimated floor area of individual buildings was combined with the material intensity to quantify material stock [34, 44, 45, 75]. Tanikawa and colleagues [18, 67] merged current digital maps (in GIS format) with old aerial photographs, paper maps and ground-level photographs to construct a four-dimensional GIS database of Japan and retrieve floor area per story and floor counts of buildings. Further, floor area per story
was multiplied by floor counts and the material intensity to quantify and spatialize materials throughout time. The four-dimensional GIS method, which was first introduced by Tanikawa, allowed for the synthesis of time as the fourth dimension into GIS analysis and tracking materials over time. In addition, material geolocation offered the ability to draw the spatial distribution of materials across a region; for example, Tanikawa showed that 80% of building materials were concentrated in 20% of land in Japan, mostly in metropolitan areas [18]. In some cases, the floor counts were not readily available in GIS databases; thus, different methods have emerged to resolve this shortcoming.

Sugimoto et al [19] conducted shadow analysis based on aerial images to estimate floor counts and complete the GIS database of a residential stock at the district level. The accuracy of shadow analysis is tied to the quality of images and varies from image to image [113]. Moreover, the feasibility of applying this method at a larger scale or to a dense metropolitan area is not clear. Marcellus-Zamora and colleagues [66] utilized images from Google Earth’s Street View to retrieve floor counts of new buildings in their studied region. For older buildings, with available height information in a GIS database, the authors converted the heights of individual buildings to floor counts assuming a floor-to-floor height of 3.6 m [66]. Similarly, Guo et al [43] converted heights to floor counts based on a 3.5 m floor-to-floor height assumption. Another study determined floor-to-floor height according to building function [114]. Other articles used simple assumptions regarding floor counts to estimate total floor area and quantify materials [32, 37]. Acquiring floor counts through manual processing of aerial or street-level images is practical at a small spatial scale or for a limited number of buildings, as in [66]; however, implementing this strategy for a city or country requires automation of the process using artificial intelligence methods [115].

Some articles calculated the average floor area of archetypes by multiplying the average floor area per story by the average floor count for every archetype. For example, Romero Perez de Tudela et al [3] estimated the average floor area of ten archetypes (see table 2) for a district located in London in the United Kingdom, and quantified accumulated timber in residential buildings. Likewise, Mesta et al [74] measured the amount of concrete, timber, brick, steel, and other materials in the residential sector of Chiclayo, Peru. Incorporating average values for archetypes instead of values for every individual building streamlines the complexity of the process and lessens computational challenges, but it may compromise the accuracy of outcomes.

**Volume from GIS analysis.** The height of a building affects the fraction of in-use materials [22]. For instance, a one-story building of 20 L × 20 W × 4 H has an equal floor area to a two-story building of 20 L × 10 W × 4 H; however, it contains double the amount of roofing materials and 33% less external wall materials. While height has sometimes been implicitly considered in building function and consequently in the archetype classification of several studies, few articles have progressed further and directly included height in the analyses [22, 29, 47, 72]. This method has been particularly popular in Austria and Germany. For Vienna, Austria, floor area per story and the heights of individual buildings were obtained from the Municipal Department’s GIS database and building volumes were estimated [29, 72]. In combination with materials intensity (mass per volume of a building), the amount of several metallic and non-metallic materials was calculated and mapped. Applying this method at a country scale, Kalcher et al [47] multiplied the average floor area per story of different archetypes, obtained from the Austrian Statistical Office, by the average height (2.5 m or 3 m). The volume of archetypes was combined with the number of buildings and material intensity of timber for the corresponding archetype to calculate accumulated timber in Austrian’s residential stock. The major barrier confronting the future of this method is that use of volume-based materials intensity is currently infrequent, as shown in table 2. Therefore, materials intensity may not be transferred and used for building stocks that are less similar to building stocks for which volume-based materials intensity is available.

**Volume and surface area of components from GIS analysis.** Geometric tools in GIS software platforms enable the calculation of the surface area or volume of building components (e.g. roof, external wall, window). Synthesizing surface area or volume with materials intensity of different components provides the opportunity to list the accumulated materials in different components. Thus, component-level material analysis aids a more efficient return of materials into the resource loop and allows the recovery paths of materials that can be retrieved from various components to be distinguished. As an example, timber from beams has a different recovery path than timber retrieved from doors and windows. Although some studies combined the surface area or volume of components with their materials intensity, similar materials from different components were summed up and reported in an aggregated fashion [4, 16, 25, 51, 63, 65, 71, 73]. Therefore, the outcomes of these studies were not useful for identifying more circular obsolescence or recovery pathways with less downgrading based on building components.

### 6.2. Top-down approaches

Top-down approaches are established based on either the relationship between driving forces (e.g. population, lifestyle, gross domestic product) and building material stock [116] or economic and trade data [13]. The benefits of these approaches are that they are less data-intensive than bottom-up approaches and they
incorporate social–materials and economy–materials interactions. Hence, one can employ these approaches to develop prospective materials stock models based on a variety of socio-economic scenarios in the future. Also, the conceptualizations that are illustrated by top-down models can be useful for policy making.

A model that used population, lifestyle and material intensity as input variables, was first introduced by Müller [50] and later employed by several other researchers [26–28, 35, 48, 56, 58, 62]. One of the metrics that represents lifestyle or living standards in a region is floor area per capita [117]. In Müller’s model, the average floor area per capita was multiplied by population to estimate the floor area of buildings; further, the floor area was multiplied by the material intensity and the total accumulated materials in Netherlands building stock were estimated [50]. Deetman et al [26] and Marinova et al [27] applied the same methodology to quantify building materials in 26 regions across the world. Although this top-down method unlocks the capability of large spatial scale analysis (e.g. country scale and global scale) it lacks information about the location of materials in a region. In addition, the accuracy of floor area per capita as one of the key variables is uncertain. Another drawback is that the population and the floor area per capita are usually aggregated over an entire building stock rather than being classified based on archetypes; thus, the end outcomes (floor area and quantity of materials) may vary significantly from real-world quantities.

As explained above, another type of top-down approach is based on economic and trade data. Fishman and colleagues [59] estimated the in-stock wood, steel, metals (i.e. copper, aluminum, tin) and minerals (i.e. stone, sand, limestone, gravel, clay) of Japan and the United States utilizing domestic production and import and export data obtained from two previous studies [118, 119]. They calculated the in-stock materials in year \( t \) by estimating consumption in year \( t \) (sum of domestic extraction and import minus export) and surviving materials from previous years. While an estimation of accumulated materials can be provided by this method, there are two shortcomings. First, the accuracy and certainty of results are tied to the quality of trade data. Second, the data are usually at a country scale, which inhibits the ability to locate and map materials.

6.3. Remote sensing approaches

A few studies leveraged satellite imagery to account for the material stock of buildings [20, 57]. He et al [20] selected 260 circular sample points (with a radius of 50 m) in Jinchang, China. Through analyzing satellite images for sample points, the total accumulated materials in buildings were roughly estimated. In another study, Hsu et al [57] explored the relationship between nighttime light images and the quantity of accumulated steel in buildings of four Japanese cities, obtained from a previous study. They developed a linear regression model to correlate nighttime light and steel in buildings. Further, the linear regression model was utilized in conjunction with nighttime light images of Taiwan, South Korea and China to estimate accumulated steel in buildings of these countries. Although this remote sensing method is rapid and beneficial in providing a broad perspective of steel in buildings, it does not offer specific information essential for circular usage of steel upon deconstruction of buildings.

In summary, bottom-up models provide more in-depth information about available materials in buildings compared to other approaches as they offer opportunities for locating materials and component-level analysis. While top-down and remote sensing approaches are viable for understanding the balance of materials in the building sector and depicting a broad perspective for policy makers, they lack detailed information, which is necessary for using stockpiled materials as secondary resources.

7. Materials inventory

One of the goals of this paper was to compile an inventory of the composition and quantity of materials. This inventory will serve two purposes. First, it can be employed to develop a global marketplace or blockchain-based network for secondary building materials. Second, it will enable the adoption of the current body of knowledge for understanding the distribution of materials in buildings and validating future studies. A total of 15 materials and ‘other’ were found in 38 of the reviewed papers (see table 3). The rest of reviewed papers (24) were not included in this inventory for the following reasons: (1) they were review articles, (2) they did not estimate the quantity of materials or (3) they estimated the total material in the building stocks. There are a few details about the composition of materials in the inventory:

- Although concrete is made from aggregate and cement, some papers estimated concrete, aggregate and cement separately.
- While one of the main ingredients of asphalt is aggregate, few papers reported aggregates separately.
- Minerals in construction include a wide range of materials. However, different papers categorized different materials as minerals. Also, some studies did not provide further specifications about what materials are considered as minerals.
- ‘Other’ included a variety of materials in different papers.
Table 3. Mass of materials estimated and reported by the reviewed papers. The unit is million metric tons Note: (NBHD and NS are abbreviations for neighborhood and not specified, respectively).

| Reference | Author(s) (year) | Spatial boundary | Country | Year of MSA | Concrete | Wood | Brick | Gypsum | Aggregate | Asphalt | Steel | Lime | Glass | Cement | Insulation | Aluminum | Copper | Minerals | Plastics | Other |
|-----------|-----------------|------------------|---------|-------------|----------|------|-------|--------|----------|---------|-------|------|-------|--------|------------|----------|--------|----------|---------|------|
| [24] Mollaei et al. (2021) | City Canada | 2018 | 15 | 3.5 | 5.5 | 2 | 8.5 | 0.5 | 1.5 |
| [32] Brads haw et al. (2020) | Country Antigua and Barbuda | 2004 | 2.9 | 0.2 | 1.2 | 0.4 |
| [34] Mao et al. (2020) | City China | 2018 | 6.9 | 331.7 | 1233.9 | 42.6 | 632 |
| [35] Gao et al. (2020) | City China | 2020 | 165 | 6 | 70 | 4 | 1 | 15 | 5 | 4 |
| [36] Gontia et al. (2020) | Country Sweden | 2017 | 35.04 | 35.04 | 43.8 | 52.56 | 249.66 |
| [37] Gontia et al. (2019) | City Sweden | 2016 | 2 | 5.8 | 12.3 | 5.5 | 4.3 | 29.7 | 1.9 |
| [39] Wang et al. (2019) | NBHD China | 2020 | 0.1 | 0.1 |
| [40] Arora et al. (2019) | Country Singapore | 2016 | 125.7 |
| [41] Miatto et al. (2019) | City Italy | 2007 | 13.7 | 0.7 | 17.6 | 0.9 |
| [42] Heeren et al. (2019) | Country Switzerland | 2015 | 527 | 31 | 203 | 17 | 276 | 2 |
| [43] Mesta et al. (2019) | City Peru | 2007 | 14.1 | 0.2 | 5.6 | 0.4 |
| [44] Han et al. (2018) | City China | 2010 | 5 | 95 | 330 | 20 | 4 | 10 |
| [45] Cheng et al. (2018) | City Taiwan | 2014 | 150.1 | 2.2 | 15.3 | 15.5 | 0.2 | 0.1 |
| [46] Condeixa et al. (2017) | City Brazil | 2010 | 51.7 | 4.3 | 1.9 | 13.2 | 2.3 | 1.5 | 0.1 | 3.2 | 0.02 | 0.49 |
| [47] Kleemann et al. (2017) | City Austria | 2013 | 152 | 7.4 | 129.2 | 5.9 | 0.1 | 0.1 | 30.4 | 0.6 | 55.2 |
| [48] Schebek et al. (2017) | City Germany | 2011 | 0.7 | 0.0 | 0.3 | 0.1 |
| [49] Musatucci et al. (2017) | City Luxembourg | 2012 | 1.1 | 0.1 | 1.6 | 0.1 |
| [50] Han and Xiang (2013) | Country China | 2008 | 290 | 3760 | 680 | 670 | 130 | 4850 | 10 | 10 |
| [51] Suhrmann et al. (2017) | City Indonesia | 2012 | 148 | 14.1 | 45.9 | 0.9 | 51 | 3 | 10.8 | 126.2 |
| [52] Schilfer et al. (2017) | Country Germany | 2010 | 684 | 328 | 2128 | 168 | 883 | 331 | 4747 | 226 | 55 |
| [53] Orlöpp et al. (2017) | Country Germany | 2010 | 1502.1 | 37.6 | 1089 | 187.8 | 37.6 |
| [54] Marcellus-Zamora et al. (2016) | District United States | 2012 | 1.9 | 0.2 | 0.1 | 0.1 | 0.2 |
| [55] Wiedenhoefer et al. (2015) | Continent | 2009 | 14.50 | 20.500 |
| [56] Fishman et al. (2014) | Country United States | 2005 | 1530 | 790 | 36.000 | 92 |
| [57] Han and Xiang (2013) | Country Japan | 2008 | 290 | 3760 | 680 | 670 | 130 | 4850 |
| [58] Hu et al. (2010) | Country China | 2005 | 559 | 5970 | 96.000 | 1600 |
| [59] Hu et al. (2010) | Country China | 2004–2008 | 1584 | 1584 | 48.5 | 651.2 | 87.3 | 0.5 |
| [60] Tanikawa and Hashimoto (2009) | District Japan | 2004 | 6.8 | 0.1 | 0.1 | 2 | 0.6 |
| [61] Lichtsteiger and Baccini (2008) | Country Switzerland | 2000 | 48.5 | 651.2 | 87.3 | 0.5 |
| [62] Bergdahl et al. (2007) | Country Norway | 2000 | 98 | 19.8 |
| [63] Hashimoto et al. (2007) | Country Japan | 2010 | 9500 |
| [64] Müller (2006) | Country Netherlands | 2000 | 780 |
In the class of papers that formed the materials inventory in table 3, five solely focused on one material [3, 30, 48, 50, 60]. Twenty-eight papers reported that concrete or a combination of aggregate and cement had the highest mass compared with the rest of the materials. This statistic shows that researchers have paid special attention to concrete as one of the highest intensity materials in buildings. However, there are noticeable challenges that require tremendous industrial, technological and academic efforts. First, traditional concrete is one of the most essential building materials and the use of alternative materials with a lower level of degradation is currently less widespread in the construction industry. The second challenge is directly related to the circular economy. Upon demolition of a building, concrete components are usually crushed and used as aggregate in various forms like recycled concrete; thus, they typically do not retain their original value. Although recycled concrete reduces waste and slows the resource loop, it does not completely prevent resource depletion because new cement and additives are needed. Strategies such as reusing and repurposing concrete components are nascent and need substantial research efforts to become industrialized. The integrity of recovered concrete components, disassembling and the shipping process along with the structural design of new buildings based on dimensions and specifications of recovered components are the roadblocks to reusing and repurposing these components.

Aggregate, brick, gypsum, stone, etc are considered construction minerals. Four papers estimated that construction minerals had the highest quantity out of the remaining materials [36, 37, 59, 60]. Gontia et al [36] considered concrete, plaster board, etc as minerals and found that minerals had the highest share in residential buildings in Sweden. Fishman et al [59] reported that in the United States and Japan, construction minerals occurred at higher percentages than wood and steel. As a variety of construction materials can be considered minerals, a more specific classification of the type of mineral materials or mineral products aids in selecting a proper strategy for recovering and returning materials or products to resource loop.

Besides concrete, minerals and a combination of aggregate and cement, brick was reported as the material with the highest share in a few building stocks. Miatto et al [73] and Mastrucci et al [71] found brick as the most predominant material in Padua, Italy and Esch-sur-Alzette, Luxembourg, respectively. Among 38 studies in the inventory, steel was quantified in 30 studies. The relatively high inclusion of steel in MSAs together with the fact that 98% of structural steel is returned to the resource loop provide a great source of data to create a marketplace for secondary steel. While the mass of plastics in buildings is significantly lower than the other materials, the building and construction sector is recognized as one of the major consumers of plastics compared with other sectors [120]. From another perspective, plastics are lighter than most building materials; thus, a different denominator than mass, such as environmental impacts, may alter the distribution of materials. As displayed in table 3, a few papers estimated plastics accumulated in building stocks but further disaggregation of the type of plastics such as PVC, LDPE, thermosets, etc was not performed [29, 52, 55, 72, 76]. The overlooking of quantification of plastics and identification of the types of plastics in the majority of reviewed articles is a substantial gap in the existing literature. To overcome environmental burdens caused by plastics pollution and waste management difficulties, the type and quantity of plastics should be estimated for building stocks.

8. Discussion

The increasing need to preserve natural resources, reduce demolition waste and explore urban mining has prompted demands for more information and knowledge about available materials in different sectors including buildings. High monetary values, increase in consumption and scarcity of some products or materials, such as critical materials and rare earth elements [121, 122], have resulted in some knowledge about their accumulation and recovery, but the MSA of buildings is a relatively new area. The remaining barriers and gaps for the progress of the field are:

- Considering the geographic location of the reviewed research papers, few to no studies have analyzed material stocks of buildings in North America, South America, Africa and Asia (except for China and Japan).
- Analysis of the embedded components in building stocks is currently overlooked. Only one study conducted a parallel analysis of material and component stocks [10].
- There is a lack of coherence in defining building function subcategories and a scarcity of differentiation between accumulated materials in structural versus non-structural components in the existing literature.
- The results of building MSAs are rarely validated.
- The limited data—especially publicly available data—about the design and construction system of buildings, especially for older stocks, not only complicates or hinders the development of building MSA models but also compromises the calculation of materials intensities of archetypes. This shortcoming will result in propagating uncertainty about material quantification from archetypes to the entire building stock.
Another barrier pertains to deficiencies of GIS data. GIS data for buildings usually do not contain detailed geometric properties of buildings such as the height or floor counts, especially in the United States. Although remote sensing methods such as LiDAR analysis [9] and the processing of space-borne sensor data [123] have been proposed to retrieve building height, this is an extra step in the creation of bottom-up material stock models. To resolve this barrier, cities and countries can consider making three-dimensional models of existing buildings at scale. Practical applications of MSA results by urban mining and waste management companies are tied to the geolocation of materials, which is more feasible via bottom-up models. Hence, thorough GIS data not only help with the development of bottom-up models but also increase the possibility of using outcomes of MSA in real-world applications.

The high concentration of building MSA research in developed countries may be attributed to the abundance of design and construction technologies such as BIM software platforms in developed countries. Knowledge about the accumulated building materials in developing countries, where the frequency of construction and demolition is higher, is essential for opening more secondary resources and fostering the circularity of the building sector. Furthermore, emphasis on analyzing building component stock and differentiation between materials accumulated in various components will increase the possibility of reuse and adaptive reuse over recycling. In addition to filling these gaps, the addressing of data barriers is important.

Policy and decision-makers can contribute to solving data barriers by instituting regulations and policies that enforce the compiling and reporting of composition, quantity and specification of construction products and materials as a part of the construction and renovation permit process. These regulations and policies would enrich publicly available building databases at city and district scales. Additionally, specifications of products and materials, such as instructions for disassembly, will aid in selecting end-of-life strategies.

9. Conclusions

Recently, discussion over the role of the circular economy in achieving the United Nations Sustainable Development Goals of Responsible Consumption and Production has increased. The major motivation of our study was to coalesce the findings of exiting building MSAs that are needed as the cornerstone of circularity for the building sector. This study evaluated the existing literature in accordance with scopes, boundaries, archetypes and material intensities and approaches to identify barriers, gaps and opportunities in the field.

A major finding of this study showed that top-down and remote sensing approaches are less time-consuming to develop and offer a broad understanding of the balance of materials in building stocks; nonetheless, they are less informative for circular economy strategies than bottom-up approaches. Also, current data deficiencies may adversely impact both the development of bottom-up MSA models and accurate determination of material intensities of archetypes. Reviewing the studies showed that the mass of concrete was higher than that of other materials in the majority of studies while the mass-based distribution of other materials varied considerably. Finally, plastics and their specific types were rarely included in MSA studies, prompting a discussion about utilizing a different denominator than mass for analyzing the material stock of buildings in the future.

MSA can aid regional policy and decision-makers. Understanding the distribution of material stocks in a region may aid in deciding on investment in technologies and equipment for construction material reuse. Furthermore, MSA outcomes can provide policy makers with information about materials that are widely available in the building stock; thus, they can consider incentives for designers and contractors. Given these benefits, it is useful to identify future opportunities that can facilitate conducting building MSA research.

Convergence of the disciplines of building science with MSA brings opportunities for assessing in-use materials of building stocks. One of these disciplines is physics-based urban building energy modeling. An urban building energy model contains three-dimensional models of hundreds of buildings; therefore, it is a rich repository of geometric properties of buildings including height, floor counts and footprint. The data from these models can be employed to resolve deficiencies in GIS data. Furthermore, classifying a building stock into archetypes is a common practice in urban building energy modeling. Available archetypes can also be utilized for archetype classification and determining material intensity for future MSA studies. We identified models at the urban scale in several US cities that can be beneficial for conducting building MSA. Moham-madiziazi et al [9] created a comprehensive database of non-residential buildings in Pittsburgh that contained geometric properties along with envelope properties (i.e. window to wall ratio and external wall materials). Also, Chen et al [124] assessed energy conservation measures of offices and retail buildings located in six districts in San Francisco based on an urban building energy model. Heiple and Sailor [125] and Cerezo et al [126] developed similar models for residential and non-residential buildings in Houston and Boston, respectively.
Moreover, Breunig et al. [127] projected floor area of residential and non-residential buildings in the State of California until 2050, which can be employed in concert with material intensity to create a prospective MSA. Another important point that can be addressed in future works is related to ownership of construction materials and products. The general concept of MSA, which is tracking construction materials over time and space, can be employed to create an ownership system in which construction materials will be tracked and collected by original manufacturers to be disassembled and reused.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

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