

Article

Promoting Circular Design in the Built Environment: Insights from the Application of Material Stock Analysis to a Case Study in Milan

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Abstract

The construction sector plays a central role in global resource depletion and waste generation, with construction and demolition activities accounting for more than one-third of total waste produced in the European Union. Despite growing interest in circular construction, one of the major barriers to large-scale material reuse is the lack of reliable information on the type, quantity, location, and availability of secondary materials during the early stages of a project. The research addresses this gap between architectural design and planning decision-making by providing a replicable workflow for urban scale circular economy strategies. This study presents the application of a spatially explicit bottom-up Material Stock Analysis (MSA) to quantify and map the embedded materials within an urban district of Milan. The adopted methodology combines municipal GIS datasets, historical cartography, building archetype classification, and literature-derived material intensity coefficients. The result is the estimation of stock amounts disaggregated by material type and the creation of a secondary material cadaster, that allows us to visualize their distributions and generate material-specific spatial analyses and heat maps. Applied to the Porta Vittoria district in Milan, the workflow reveals that masonry accounts for over 66% of the total embedded mass, underscoring the need to factor the reuse of masonry and brick materials into the early design phases, from material selection to architectural concept. Ultimately, the study equips architects, urban planners, and policymakers with decision-support information to steer design and governance toward circular future cities.

Keywords: circular design; secondary materials; material cadaster; bottom-up approach; building stock



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1. Introduction

Between 2000 and 2019, domestic material consumption, defined as the amount of raw materials directly used in production processes within a country, increased by 66 per cent, tripling since the 1970s, to reach 95.1 billion metric tons [1]. At the same time, the spatial footprint of urbanization has continued to expand. According to an analysis of 681 cities, the average built-up area per capita increased from 161 m² per person in 1990 to 169 m² in 2020 [2]. Combined with ongoing demographic trends characterized by both population growth and aging [3], these dynamics are expected to further accelerate construction activity in the coming decades. Such trends risk undermining the achievement

of several Sustainable Development Goals (SDGs) while exacerbating social, economic, and environmental inequalities across both developed and developing countries.

Evidence of the resource pressure generated by the built environment is also reflected in waste statistics. In the European Union, construction and demolition waste (CDW) accounts for more than one third of total waste generation (Figure 1), representing approximately 37.5% by weight of all waste produced [4].

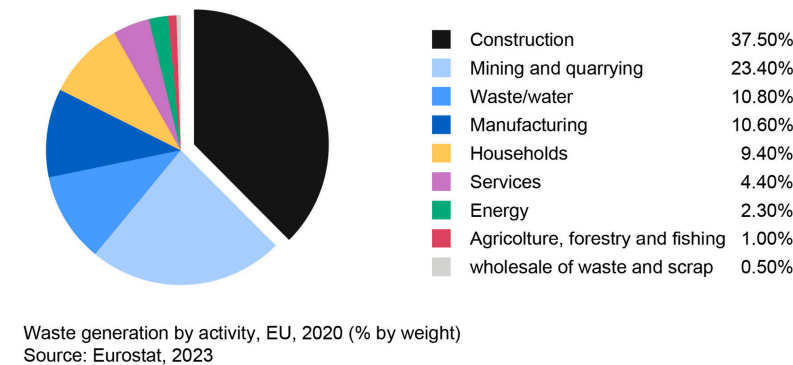


Figure 1. Waste generation by activity in EU in 2020. Source: Eurostat [4].

1.1. Demolition Waste, Urban Mining and Material Reuse

The circular economy aims to reduce material consumption by intervening across the entire value chain [5], reducing the extraction of virgin resources [6] through a hierarchy of strategies (reuse, repair, remanufacturing, and recycling) and more efficient allocation of existing materials.

At its most practical level, reuse is a waste management strategy that utilizes reclaimed materials or components in their original or near-original form for new purposes, thereby maintaining their economic value and preserving the resources initially invested in their production [7].

Today, urban materials will become tomorrow's waste, but they could serve as a future resource if their embodied value is recognized and their recovery (through recycling or reuse) is enabled through urban mining, defined as the systematic extraction of anthropogenic materials from urban areas [8–10]. Urban mining encompasses actions and technologies to recover wasted or unused materials, food, water, and energy from cities, exploiting large resource stocks in buildings, infrastructure, and landfills. This approach postulates that cities can generate sufficient secondary resources for large-scale raw material production from inherent material stocks [11].

As stated by Koutamanis et al. [12], urban mining and material reuse require the prior quantification of the material stock to be reclaimed, more than the application and comprehension of better recovery techniques [13]. Therefore, it is necessary to know how much secondary material is available and what type, where, and when it becomes available. This calls for city- or region-wide planning tools: secondary material cadasters [8] are emerging as a key solution. These are geospatial databases that map the distribution of material stock contained in existing buildings. They are the first step to understanding the future availability of secondary materials and implementing the process of reclaiming them.

There are two main methodologies to quantify the material stock embedded in existing buildings: the deductive bottom-up and inductive top-down approaches [14].

The top-down approach builds on the mass-balance principle that the change in the stock is the result of the difference between inflows and outflows of a material over time [15]. This methodology works through a flow-driven approach [16], estimating the material flows entering and leaving the system, as shown in the studies of Marinova et al. [17], Krausmann et al. [18], and Hsiao et al. [19].

On the other hand, the bottom-up process aims to quantify the materials contained within a system by counting its constituent elements. This methodology is driven by information derived from stock inventory: all items containing a specific material are counted and multiplied by the material intensity [20]. Consequently, the data modeling approach is quite labor-intensive, but allows for greater accuracy than the top-down approach, in terms of composition, intensity, and geographic distribution [21].

Due to the large amount of data required, the scope of bottom-up studies is often narrowed down to a smaller geographical scale (city level or below), a specific year, specific materials, and specific stocks' categories (e.g., many studies occur on residential buildings) [20].

As shown in the systematic review on building stock mining for a circular economy by Rajaratnam et al. (2023) [22], many bottom-up studies have been developed for different cities. Table 1 shows an excerpt of the reviewed articles on the matter and their specific area of analysis.

Table 1. Selected bottom-up MSA studies conducted at the urban or district scale.

Study Area	Ref.	Authors	Year	Study Definition
Salford (UK); Wakayama (Japan)	[23]	Tanikawa and Hashimoto	2009	Building/infrastructure asset
Vienna (Austria)	[24]	Kleemann et al.	2017	Building
Melbourne (Australia)	[25]	Stephan and Athanassiadis	2017	Building
Melbourne (Australia)	[26]	Stephan and Athanassiadis	2018	Building
Chiclayo (Peru)	[27]	Mesta et al.	2019	
Shenzhen (China)	[28]	Wang et al.	2019	Building
Leiden (Netherlands)	[29]	Verhagen et al.	2021	Building
Tampere (Finland)	[30]	Huuhka and Kolkwitz	2021	Grid cell 250 m × 250 m
Xiamen (China)	[31]	Liu et al.	2022	Building/dwelling
Shenzhen (China)	[32]	Wu et al.	2016	Building
Shenzhen (China)	[33]	Mao et al.	2022	Grid 500 m × 500 m
Taipei (Taiwan)	[34]	Cheng et al.	2018	Building polygon
Vantaa (Finland)	[35]	Kolkwitz et al.	2023	Plot level
Odense (Denmark)	[36]	Lanau and Liu	2020	Building
Odense (Denmark)	[37]	Li et al.	2022	
Leeds, Bradford, Manchester (UK)	[38]	Ajayebi et al.	2020	Building
Bradford (UK)	[39]	Ajayebi et al.	2021	Building
Esch-sur-Alzette (Luxembourg)	[40]	Mastrucci et al.	2017	Building
Padua (Italy)	[41]	Miatto et al.	2019	Building

Table 1. Cont.

Study Area	Ref.	Authors	Year	Study Definition
Canberra (Australia)	[42]	Schandl et al.	2020	Building
Philadelphia (USA)	[43]	Marcellus-Zamora et al.	2016	Building
Philadelphia (USA)	[44]	Marcellus-Zamora et al.	2020	
Sheffield (UK)	[45]	Arbabi et al.	2022	Building component

1.2. Scope and Aim of the Work

Despite the overall European concentration of studies, Italy remains relatively under-represented in the literature. This is significant considering the scale and characteristics of its building stock, which is largely privately owned [46] and often characterized by long lifespans and incremental transformations. At the same time, Milan is currently experiencing a renewed phase of urban development and construction activity, leading to increasing material demand and making the analysis of a Milanese district a relevant contribution to address this geographical gap.

This study presents a bottom-up assessment of the building material stock of a district in Milan, resulting in a resource cadaster that maps the distribution of materials potentially available for recycling and reuse, providing architects, planners, and policymakers with information to support urban mining strategies.

2. Materials and Methods

The bottom-up MSA to estimate the amount and spatial distribution of building materials in the city includes several steps. This section details the overall modeling approach and a description of the steps. Figure 2 illustrates the overall modeling approach that was developed and utilized in this study.

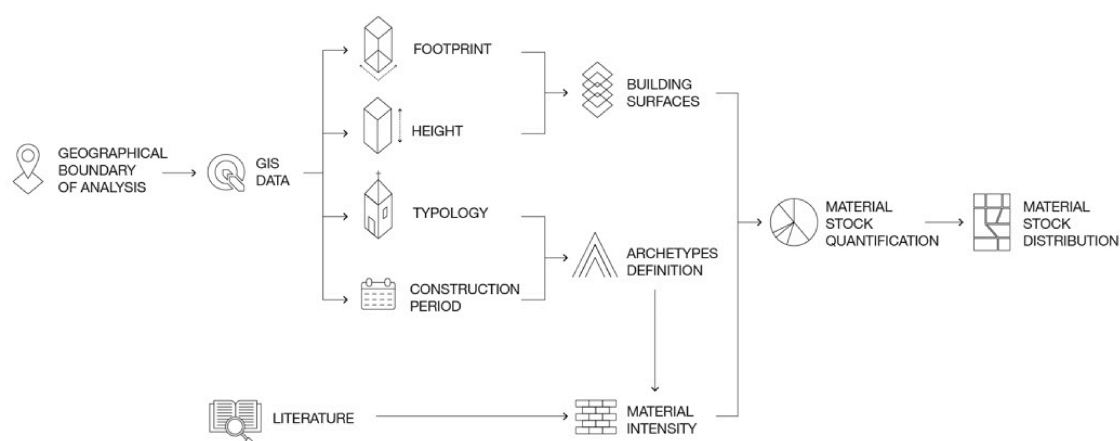


Figure 2. Bottom-up methodology.

2.1. Boundary, Data Collection, and GIS Modeling

The first step is to set the geographical boundary of the analysis, usually a district or a city. Then, the process foresees the creation of a geo-localized inventory of buildings [36]. This kind of inventory often exists in the form of Geographical Information System (GIS) data, gathered from usually accessible local databases. GIS, as a tool for handling, processing, and analyzing large amounts of geospatial data, allows for high spatial resolution and improved understanding of the physical composition of the built environment stock.

In particular, GIS enables the extraction, analysis and manipulation of spatial data and information, such as building footprints and floor area, as well as the clusterization of the stock into building archetypes, and the spatial disaggregation of material quantities at the individual building level.

The integration of GIS data into the bottom-up approach was developed by Tanikawa and Hashimoto [23] and has now become a well-established practice in the panorama of bottom-up studies.

2.1.1. Geometric Data

Then, geometric datasets are extracted from the GIS database: though the type of information included on buildings varies across cities and countries, it is possible to retrieve footprint area and perimeter, height, function, and year of construction for each building. To estimate the total gross floor area, the building footprint is multiplied by the number of floors, which—if this information is not included in the GIS database—is derived from the building's height divided by the average height of a single story.

2.1.2. Year of Construction

The year of construction must then be identified for each building to define age classes (cohorts). While some GIS databases include this information, others do not. In such cases, construction periods can be reconstructed by incorporating historical sources and cadastral maps.

2.1.3. Material Information

Most GIS databases do not include “bill of material” information, and studies rely on average material intensity coefficients derived from literature and building archetypes, which facilitate the data modeling: the heterogeneous datasets of buildings are thus homogenized by weighing each archetype by the number of buildings fitting the archetype [47].

2.2. Archetypes Definition

The archetypes are a representative subset of buildings that exemplify the construction techniques used across different typologies and ages of a certain area. The use of archetypes has been introduced for modeling energy performance of building stocks [48–50] and is now common for material stock studies [20]. For each archetype, material quantities can be derived for individual building components from literature, surveys, or reverse engineering, and then extrapolated across all buildings in the group, making large-scale assessment both feasible and replicable.

2.3. Material Intensity

The archetypes allow direct translation from geometrical data to material quantities through the definition of material intensity (MI), defined as the mass of construction materials per unit of building floor area (e.g., kg/m²), as developed by Gontia et al. [51] and Heeren and Fishman [52]. Each archetype is subdivided into specific elements (e.g., roof, load-bearing walls, etc.). For each element, the material intensity is identified (through studies, professional knowledge, or redrawing), to calculate (e.g., concrete, timber, steel) the average mass per unit for each material [53].

2.4. Material Stock and Material Cadaster

By merging the GIS database with typological material intensity coefficients, it is possible to calculate the overall material amount of each building material within a given boundary and its spatial distribution, known as a cadaster of secondary materials.

The cadaster enables a granular spatial characterization of the built environment, localizing resource accumulations (e.g., concrete, steel, timber, or bricks). The framework provides important information on materials that can help to set priorities for recovery, the design of effective reclamation systems, and recycling logistics [8].

3. Results

The described spatially explicit bottom-up analysis has been applied in the district of Porta Vittoria in eastern Milan as of 2025. The model relies on georeferenced GIS models, as explained in the previous chapter.

3.1. Boundary

The study area has been delineated to include NIL 26 and a portion of NIL 28 (NIL stands for *Nucleo di Identità Locale*, an administrative boundary used by the Municipality of Milan), as shown in Figure 3. The selected area covers approximately 283 ha, corresponding to approximately 1.56% of the Municipality of Milan. Despite that, it accounts for about 4% of the overall population and 4.3% of its building stock, indicating a relatively high concentration of urban stock.

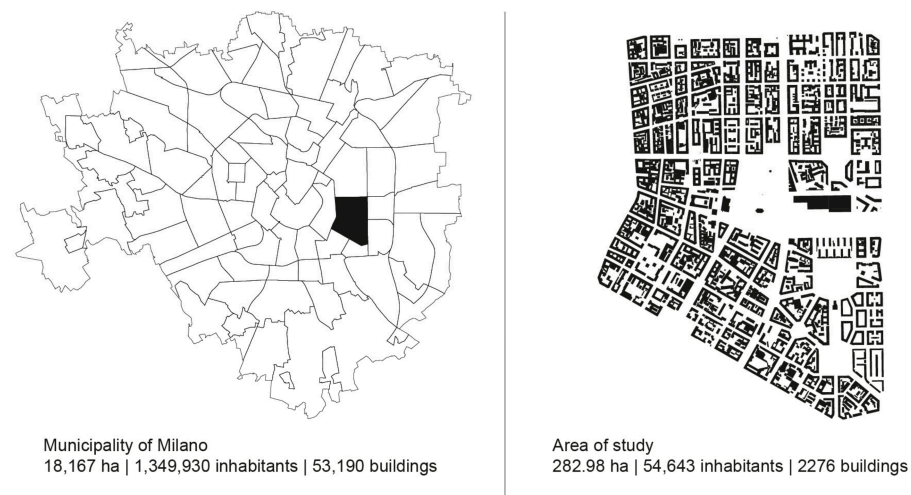


Figure 3. Location and data of the area of study.

The area, selected for the relative homogeneity of its building typologies, can be considered a representative sample of Milan's urban fabric, making it suitable for testing methodologies related to building stock characterization and secondary material supply assessment.

3.2. Building Surfaces

Geometries data have been retrieved mainly from the Milan Municipality geospatial dataset and the Lombardy Region Geodatabase [54]. Some integrations and comparisons have been made with the OpenStreetMap open data platform [55] and with the TABULA-EUBUCCO [56] (the relative Italian dataset "v0_1ITA").

This process considered the definition of these datasets, prioritizing the local Milan/Regional databases, as they are more granular, and using the EUBUCCO and OSM secondarily to fill the gap between eventual lacking information (especially heights and destination of use). It was particularly crucial to control and define residential buildings, the subject of this study, which may present as street-level commercial space, therefore possibly being differently defined in various datasets; a similar process was conducted to better refine the "other" classification, maximizing the total analyzed buildings.

The GIS dataset provided the footprint area and height. Therefore, the total gross floor area of each building was calculated by multiplying each footprint area by the number of stories, which were derived from the height divided by the average height of a single story. The average height depends on the building function, derived from land use information, present in the used database.

3.3. Temporal Classification

A comprehensive age classification for each building has been carried out to set the archetypes according to the different building technologies (Figure 4a). Unfortunately, the Milan Municipality geospatial dataset did not comprise specific information regarding the construction year for each building; it comprised all municipal technical maps redacted from 1884 (1884, 1910, 1930, 1946, 1956, 1965, 1972, 1990, 2000, 2006, 2012). Through the manual fusion of the historical raster images with the building geometries, a distinction of the age clusters was conducted, as performed by Miatto et al. (2019) [41]. This method is sufficiently agile for small geographic boundaries, such as the described case-study, but quite demanding for more extensive ones.



Figure 4. Spatial distribution of the different cohorts (a) and of the different building uses (b).

3.4. Building Use

In parallel, the use of each building was retrieved and corrected where necessary. Figure 4b shows the prevalence of residential buildings.

3.5. Archetypes

As described, the buildings within the study area have been classified through a GIS-based overlay and comparison of the historical maps. However, the number of historical thresholds (derived from different technical maps) exceeded the meaningful distinctions in construction technology, as described in TABULA and in other technical manuals.

Therefore, archetypes were grouped into broader time periods that better reflect their construction technology: seven residential, seven public offices (school, hospitals, administrative buildings, etc.), seven commercial, and one industrial. The result is shown

in Figure 5. Buildings related to transportation, leisure, and religion cover only a minor share of the total built volume of the study area and have therefore been neglected.

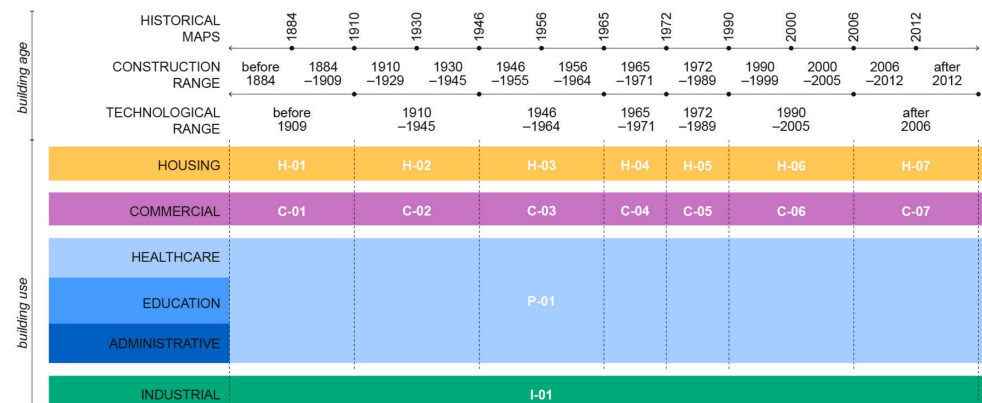


Figure 5. Grouping of the different building archetypes according to year of construction.

An adapted version of the methodology developed by Miatto et al. [57] for the Italian building stock was adopted. The TABULA project, born to classify the energy efficiency of residential building typologies in different European countries [58–60], served as the primary reference for defining building technologies. The archetypes have been redrawn in AutoCAD LT 2024, the drawing environment developed by Autodesk. The definition of these reference plans was informed by a review of historical construction and housing manuals [61–65]. An example of a residential archetype is provided in Figure 6.

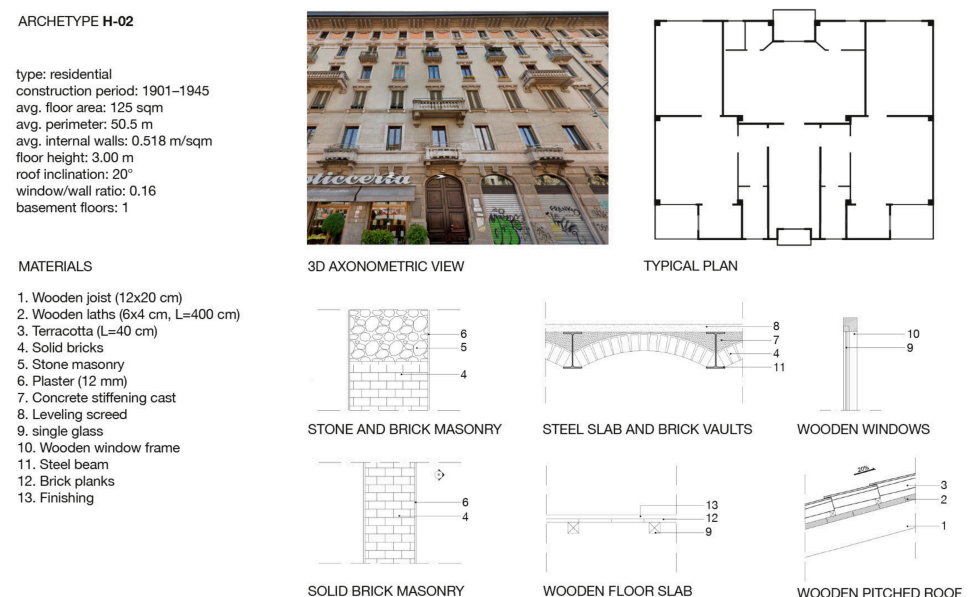


Figure 6. Characteristics of archetype H-02.

The geometric definition of each archetype was parameterized through a set of variables informed by literature sources, calculations from the reference plans, and Italian regulatory requirements. Parameters include story height, window-to-wall ratio (1:10 window-to-floor area), roof pitch (including flat-roof adjustments consistent with TABULA), number of basement stories, building perimeter, structural footprint ratio (computed as the ratio between the plan area occupied by structural elements and the gross floor area: m^2/m^2), internal partition ratio (m/m^2), and number of internal doors.

These variables allow the modeling of individual components (columns, walls, windows, doors, etc.), for which material compositions were assumed to compile a bill of materials and compute average material mass intensities (kg/m^2) for each archetype.

3.6. Data Modeling Process

All geometric data have been extracted from the GIS model and exported to a calculation environment (Excel was selected for its accessibility and ease of visualization), where the Material Stock Analysis has been performed. Afterwards, an extensive data-cleaning process was conducted to identify and correct geometric inconsistencies, remove duplicates, and fill in missing information where possible.

As a result, the number of total analyzed geometries was reduced from 2414 to 2276. This ensured a consistent geometry and information database, correcting possible overlapping or spurious geometries and harmonizing information from different datasets, including building age (Municipality of Milan historical maps), height (from OSM, EU-BUCCO, and the Municipality of Milan), and land use destination, which is the main proxy for archetype classification and material intensity definition.

The above-described process yielded the total volume of embedded materials, as illustrated in Table 2.

Table 2. Total volume and mass of embedded materials.

Material	Volume [km^3]	Volume [%]	Mass [ton]	Mass [%]
wood	240	2.11%	194,039	1.10%
masonry	8177	72.09%	11,848,091	66.92%
metal	9	0.08%	44,278	0.25%
glass	10	0.09%	23,836	0.13%
ceramic	0	0.00%	0	0.00%
textile	1	0.01%	913	0.01%
mineral	1347	11.87%	2,417,412	13.65%
polymer	84	0.74%	6048	0.03%
composite	0	0.00%	0	0.00%
concrete	1477	13.02%	3,170,537	17.91%
Total	11,343	100.00%	17,705,153	100.00%

An additional material classification was carried out according to the concept of shearing layers introduced by Duffy and later developed by Brand [66]. This framework is particularly useful as it allows a clear interpretation of each material's role within the building system.

Moreover, it highlights the differing potential for reuse and the variable replacement frequencies associated with each layer, depending on factors such as exposure, renovation, evolving performance, or esthetic requirements. The distribution of material stock across the shearing layers is presented in Table 3.

Table 3. Distribution of the overall building stock across Brand's shearing layers.

Material	Volume [km^3]	Volume [%]	Mass [ton]	Mass [%]
Stuff	0	0.00%	0	0.00%
Space	8	0.07%	5003	0.03%

Table 3. *Cont.*

Material	Volume [km ³]	Volume [%]	Mass [ton]	Mass [%]
Service	928	8.18%	1,393,703	7.87%
Structure	9073	79.99%	13,897,227	78.49%
Skin	1334	11.76%	2,409,220	13.61%
Total	11,343	100.00%	17,705,153	100.00%

3.7. Spatial Distribution

The material quantities obtained for each unique building geometry were subsequently re-imported into QGIS to visualize their spatial distribution and concentration across the study area, as illustrated in Figure 7 for masonry and concrete.



Figure 7. Spatial distribution of concrete (**left**) and masonry (**right**) referred to the boundary of analysis (thousands of cubic meters).

A complementary visualization of the results is provided by material-specific heatmaps, produced for masonry, concrete, wood, metals, and insulation.

Masonry exhibits a distribution that closely reflects the construction-age patterns and well aligns with the historical classification reported in Figure 8a. Buildings closer to the city center are more likely to incorporate masonry components and to present larger volumes. The highlighted area corresponds to a cluster of tall residential buildings (10–13 stories), constructed between 1884 and 1910, with volumes nearly twice those of the surrounding stock.



Figure 8. Heatmap of building materials: masonry (a), concrete (b), metal (c), insulation (d).

Concrete shows an opposite pattern. Its spatial distribution is substantially more homogeneous than that of masonry (Figure 8b), perhaps because it is extensively used in underground levels.

By contrast, metals display a more dispersed distribution (Figure 8c). Despite the comparatively small quantities involved, no clear spatial trend emerges, except for higher values in areas associated with former factories and industrial facilities.

Finally, insulation materials largely follow an age-driven distribution: newer buildings, which incorporate greater insulation volumes, are located in the southern portion of the study area (Figure 8d).

4. Discussion

Estimates of building materials stock in cities have been gaining importance in the literature, but the lack of methodological standardization leads to non-easily comparable results [41]. Benchmarking the estimated stock of Porta Vittoria against other studies confirms that the selected area has an above-average material stock per capita (376 t/cap), exceeding most values reported in the literature (Table 4).

Table 4. Comparison with other cities.

City	Mass per Inhabitants [ton/cap]	Scope of the Study	Reference
Milan Porta Vittoria	376 (2025)	Buildings	this study
Padua	209 (2007)	Buildings	[41]
Vienna	210 (2013)	Buildings	[24]
Paris Region	204 (2013)	Buildings + networks	[14]

Table 4. *Cont.*

City	Mass per Inhabitants [ton/cap]	Scope of the Study	Reference
Gothenburg	112 (2016)	Buildings, roads, and pipes	[67]
Kitchener/Waterloo	164 (2018)	Buildings, roads, sidewalks	[68]
Bochum	208–232	Buildings	[13]
Taipei	68 (2014)	Total buildings	[34]
Thane (India)	46.1	Permanent buildings	[69]
Chiclayo (Peru)	47–55 (2007)	Residential buildings	[27]
Salford/Manchester	111 (2004)	Buildings and infrastructure	[23]
Wakayama	247 (2004)	Buildings and infrastructure	[23]
Grenada	112.4 (2014)	Buildings	[70]

The high material stock per capita can be partially explained by the characteristics of the study area (see Section 3.1): despite covering only 1.56% of the Municipality of Milan, the study area accounts for approximately 4% of its population and 4.3% of its building stock. Furthermore, the building footprint of Porta Vittoria covers 589,790 m² out of 2,300,770 m² (26%), which is significantly higher than the municipal average (15%), indicating a denser built fabric with less open space per unit of land, which directly contributes to the above-average material stock per capita.

Limitations and Future Outlook

As outlined above, the method requires buildings to be grouped into “archetypes” based on their function and construction period. This forced homogenization overlooks the real heterogeneity of individual structures, leading to systematic errors.

Furthermore, to achieve a reasonable level of approximation without excessive generalization, archetypes are often study-area-dependent, manually extracted from floor plans or technical manuals, which makes it problematic to apply these models at national or continental scales.

An additional limitation concerns the reliability of the input data: cadastral databases and GIS maps may be incomplete or outdated with respect to the actual built environment, particularly in dynamic urban contexts. This issue is especially critical in large and rapidly evolving metropolitan areas, which are at the same time the most resource-rich and analytically interesting targets for urban mining studies. In Milan, for instance, a few buildings constructed after 2015 are not yet recorded in the GIS database.

While accurate, the proposed method is very labor-intensive in terms of manual data entry. Future research directions will therefore focus on automating the process using artificial intelligence, for instance, by means of automated visual recognition of building features such as window openings, façade materials, and public space materials. Such an approach has the potential to significantly reduce the burden of the manual work currently required, while also improving the scalability and transferability of the method across different geographical contexts.

In the present study, a machine learning and image recognition method was initially tested with the aim of automating the temporal categorization of buildings based on raster images of historical maps. However, early-stage experiments delivered limited reliability, leading to a more conservative approach based on the manual integration of historical maps into the GIS database.

5. Conclusions

The study results in the creation of a resource cadaster mapping the distribution of building materials with potential for reuse. This tool provides a knowledge base that can support architects, designers, planners, and policymakers in developing strategies for material reuse and urban mining. It delivers a baseline dataset for a future dynamic material flow model that projects the future availability of building materials over the coming decades.

Despite the limitations and approximations discussed above, the proposed method remains highly flexible, enabling the expansion of the study area through the integration of additional building data. Indeed, a city-wide simulation for Milan is currently underway by the authors. Its objective is to produce a comprehensive, spatially explicit mapping of material stocks at the urban scale, thereby extending the method's applicability and strengthening its value as a decision-support tool for circular-economy planning at the metropolitan level.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/app16125864/s1>.

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Abbreviations

The following abbreviations are used in this manuscript:

MSA	Material Stock Analysis MSA
CDW	construction and demolition waste
GIS	Geographical Information System
NIL	Nucleo Identità Locale

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