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Urban mining potential in Serbia: Case study of residential building material stock

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ABSTRACT

As governments worldwide attempt to develop sustainable waste management strategies, massive amounts of waste have been accumulating. However, developing an effective waste management strategy requires a thorough understanding of waste types and quantites. The existing efforts to identify waste flows in the built environment are unsuitable for countries with non-reliable statistics as they mostly use location-specific parameters such as data on construction, renovation, demolition activity, and generation rates from the literature. The types and quantities of materials embedded are rarely considered. This study aims to fill the identified gap by estimating the quantities of different material types embedded in Serbian residential building stock. It will do so by calculating the volume and weights of building elements and their materials using information from a detailed building stock typology. The results show that the amounts of materials embedded vary significantly from district to district, ranging from 10 in Toplička District to 96.9 million tons in Belgrade. The mineral materials are the highest contributors to the material embedded, implying that future waste management strategies should focus on them. Apart from the formulation of location-specific circular economy and waste management strategies, these results may be useful for planning energy efficiency retrofitting activities, deconstruction and reversible design strategies.

1 Introduction

The construction industry has a considerable impact on national economies, meaning that economic growth is strongly related to the construction sector's growth. In the European Union (EU), this sector alone produced 10.6% of the GDP, 6.2% of all jobs, and achieved investments of 1,402 billion euros in the 2020 [1]. Building construction and operation also accounted for 37% of all energy-related CO_2 emissions and 36% of the world's energy demand [2].Even the waste generated by these activities should not be disregarded because it accounts for more than one-third of all waste [3].

In addition to the economy, the effects on society and the environment also increase as the construction sector expands. And even despite the COVID-19 pandemic, significant investments are predicted in this sector [4]. These investments suggest that primary raw material extraction will increase and that product consumption will rise, increasing the total stock of construction materials. At the same time, the existing stock, especially the materials embedded in the residential building, is either at the end of its service life or is energy inefficient, and the stock requires significant reconstruction or retrofitting. And finally, an increase in investments also implies a higher degree of urban development, which may lead to the demolition of old and vacant buildings, especially in the inner-city areas.

For these reasons, governments have been creating funding programs, policies, and regulations aimed at more prudent energy production and use, efficient natural resource consumption, and more sustainable construction and demolition waste management. For instance, under the Green Deal initiative, the EU has gathered several strategies and action plans to achieve climate and resource neutrality by 2050 [5], such as the Renovation Wave Strategy, which aims to double the energy renovation rate of buildings by 2030 [6], a New Circular Economy Action Plan, which focuses on sustainable consumption of resources and reduction of waste [7] and the forthcoming Sustainable Built Environment Strategy [5].

However, the incorporation of these strategies within the national, regional, or even local housing and waste management policies will require the knowledge of the material stock embedded in the buildings, especially the content and quantity, as well as the predictions of building stock dynamics. To define the material stock database, i.e., the material cadastre, scientific literature distinguishes two approaches: top-down and bottom-up.

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The top-down approach utilizes data from national statistical records to estimate the material flows, which are determined annually as the difference between the inputs and outputs of materials [8]. This approach was used in multiple disciplines in the scientific literature, either to estimate the current material flow or to predict future material flows. One of the first uses of this approach in the built environment was in Japan to estimate the present construction minerals embedded in buildings and roads [9], [10], and in the United States to predict the amount of construction and demolition waste (CDW) until 2052[11] depending on the percentage of waste generated during construction and the service life of materials. Similarly to the United States, a more recent study has included a top-down approach to estimate the amount of CDW from buildings and civil works in India [12]. Although predominantly used for estimating material flows on a national level, this approach mainly focuses on stock additions, thus failing to provide important information such as the spatial distribution, quantities, types, and service life of embedded materials. Without this knowledge, it is impossible to create an effective renovation, demolition, or CDW management strategy that specifically targets buildings of a certain age or structure.

To overcome this, scientists recommend a bottom-up approach or a combination of the two. The idea behind the bottom-up approach is to divide the material stock into different structures, calculate their physical characteristics and use material intensity coefficients or ratios [8] to calculate the amount of the material embedded, i.e. the material intensity. Experts estimate material intensity coefficients [13–15] or calculate them in numerous case studies around the world. When calculated, these coefficients are derived from structures geometries, in most cases, buildings. The physical features of the structures may be estimated in several ways: 1) modeling of different parameters to determine the average size of the floor area of the stock, such as population and housing lifestyle [16] or per capita floor area, local GDP and lifetime of dwellings [17], 2) investigating municipal records and building plans [18], [19], and 3) spatial analysis via Geographic Information System (GIS) [14], [20]–[22]. The material intensity coefficient data are available for buildings in Esch-sur-Alzette, Luxembourg [21], Rio de Janeiro, Brazil [23], Vienna, Austria [20], [24], and Padua, Italy [14] at the city scale, and Germany[18], [25], Sweden [19] and Luxembourg [22] at the national scale.

Except for Kleemann et al. (2016), who combined existing and new building plans and literature, most of these coefficients were calculated from selected case study buildings from different construction periods [18], [19]. Although material intensity coefficients for a particular building offer a high degree of accuracy, they cannot be used as representatives of the entire set of buildings built in that period or at a specific location. For instance, Gontia et al. (2018) investigated 4000 real estate ads and 1000 building plans from 30 municipalities (out of 290) to establish 12 typical single-family and 34 multi-family house buildings.

On the other hand, the studies that calculate material intensity coefficients from statistical records may be used when greater accuracy is required. Still, their application is limited to countries with reliable statistics. In addition, the findings in these studies served to emphasize how sensitive these coefficients are to location-specific factors such as environmental conditions, architectural characteristics, construction techniques and materials applied, and rate of economic growth, highlighting the need for additional case study research on this subject.

To overcome these shortcomings, this study will build on previous knowledge, but instead of using municipal records or expert knowledge, it will use typical buildings (building typologies) at the national scale to calculate intensity coefficients and quantities of different materials embedded in these buildings. The calculation of material quantities may be further used in dynamic residential building stock modeling and in the estimation of more precise amounts of waste that may be generated during the renovation or demolition activity of these buildings. This can, in some cases, affect the decision whether to refurbish or demolish [26]. In addition, the study will focus on the calculation of embedded material quantities at the district level instead of the national level as CDW is often managed regionally. In this way, these regional material intensity coefficients will provide a robust base for further modeling of the residential building stock and CDW flows and different sustainability assessments of CDW treatment options.

2 Methodology

The overall approach of the suggested methodology for the estimation of residential building material stock and material intensity coefficients is based on inventory analysis of typical buildings within a building stock. Typical buildings are representatives of buildings classified into cohorts that were built using construction techniques and materials from the same period and which share similar architectural features. They are usually established on a national scale, as are the ones for residential buildings developed for 21 European countries within the European Project Tabula [27]. If these typologies do not exist within one country, when developed, they should at the very least comprise the layouts and cross-sections of typical buildings and details of building construction and applied materials.

The inventory analysis that is conducted on typical buildings follows the approach and the methodology presented in the thesis by Nadaždi (2022). These include several initial steps performed for each building type to create a unique database: generation of a typical building element list (walls, columns, openings, stairs, etc.), identification of the elements' dimensions (width, height, and length), location within the building (basement, ground floor, 1st floor, attic, etc.), and quantity, identification, and classification of material types. These materials were grouped into four categories: 1) minerals, 2) non-minerals, and 3) metals, to facilitate easier calculation and representation of the material embedded in the residential building stock and for comparison with the existing research. While the mineral category included materials such as concrete, brick, blocks, tiles, plaster, glass, gypsum, etc., non-minerals included plastic, polystyrene, textile, and wood. Although metals can also be considered non-minerals, they were separated because of the substantial differences in how they are treated at the end of their service lives.

The next step of the suggested methodology was to calculate the area, volume, and mass of each individual component of a typical building. Two methods were used to compute the element's area: directly measuring from drawings using a built-in CAD function or multiplying two dimensions and deducting openings where necessary (mostly in cases of walls and slabs). The area and third dimension are multiplied to determine the volume of construction elements, while the volume and material density are multiplied to determine the elements' mass. Densities for most materials are taken from the MASEA online database (Fraunhofer Institute for Building Physics in Holzkirchen et al.

n.d.); those that were not found there were found in textbooks or technical data sheets.

Following this, the total mass of each material category contained in a single typical building, and the accompanying material intensity coefficients were determined. The first was determined by multiplying the number of elements and their masses, then aggregating these values based on material types. Dividing these aggregated masses yielded the material intensity coefficients for a typical building.

While the computation of material category masses for typical buildings was based on building typologies, estimating material categories embedded in buildings per district needed statistical records on the number of buildings per building type and district. However, national statistics frequently do not keep track of the number of buildings constructed in specific districts during a particular construction period but rather the number of dwellings in them. In these instances, it was necessary to follow the assumption that a proportion of buildings per district follows a distribution of dwellings per district, especially for multi-family house buildings. Another assumption that was made was related to the classification of single-family house buildings. While typologies distinguish between two different single-family house building types, free-standing and in a row, statistical data only distinguishes between buildings with one or two dwellings. In these instances, it was presumed that all single-family house buildings are free-standing because the percentage of single-family house structures in a row is insignificant [29].

Additionally, it should be emphasized that this study's focus on material types is limited to key structural and non-structural components and leaves out a number of building components for which it was challenging to gather information from building typologies. These include foundations, shades, window sills, lintels, the mortar between blocks and bricks, chimneys, installation works, and fixtures, etc. This limitation could result in an underestimation of the composition results, especially regarding the quantity of particular constituents like non-minerals and metals.

3 Results and Discussion

In this study, the proposed methodology was used to estimate the quantity and composition of residential building stock materials in Serbia in order to investigate the potential contribution to the circular economy value chain when these materials become waste. With a population of 6.9 million and an area of 88499 km^2, Serbia is divided into 30 districts (five of which belong to the Kosovo and Metohija region) [30]. In its transition to the EU, Serbia has adopted several environmentally-oriented strategies and initiatives, especially towards a circular economy, waste management, and energy efficiency renovation. However, a rate of only 0.3% of GDP investment in environmental protection [31] compared to the EU average rate of 1.8-2.0% of GDP during the previous fifteen years [32] suggests that Serbia needs these carefully planned initiatives.

In addition to this, Serbia´s residential building stock is very old and energy inefficient. Since residential buildings built before 1980 account for around 70% of the whole building stock in Serbia that was built before 2011 [29], it is anticipated that renovation and demolition operations will rise in the future. This indicates that certain residential buildings, especially those constructed after World War II, are rapidly approaching the point at which their demolition is likely. This is further supported in the Strategy on National Housing for the period 2022—2032, which sets the renovation objective of up to 30% of the buildings whose amortization period expires in 2032 [33].

Serbian residential building stock is represented in the National Typology made by [29] within the Tabula project. It is characterized by 26 building types grouped under seven cohorts, i.e., periods of construction (from A to G) and building types (from 1 to 6). When it comes to the period of construction, they included all residential buildings built before 2011, while building types were divided into single-family (free-standing (1) and in a row(2)) and multi-family house buildings (free-standing buildings (3), lamella (4), in a row (5), and high-rise buildings (6)) [29].

Considering the fact that most of the renovation or demolition activities in the coming years will be conducted on residential buildings aged above 40 years, this study will cover only buildings built between 1946 and 1990. To that extent, Table 1—

Table 3 summarizes the total amounts of each material category (mineral, non-mineral and metal) per different types of buildings.

Table 1. Total mass of material categories in one typical single-family house building built from 1946—1990 (in tonnes)

	1946—1960		1961—1970		1971—1980		1981—1990	
	C1	C2	D1	D2	E1	E2	F1	F2
Minerals	200.93	539.40	452.86	209.13	489.55	378.41	321.43	356.20
Non-minerals	193.15	515.31	438.99	196.33	484.72	365.83	316.99	351.09
Metals	5.13	23.67	10.83	10.71	4.83	12.58	4.43	5.11

Table 2. Total mass of material categories in one typical multi-family house building built from 1946—1970 (in tonnes)

	1946—1960				1961—1970			
	C3	C4	C5	C6	D3	D4	D5	D6
Minerals	1,218.40	1,230.36	1,517.94	4,905.32	2,155.31	1,403.31	1,892.91	5,594.62
Non-minerals	26.03	31.40	30.61	373.31	68.24	91.08	85.68	552.63
Metals	28.32	1.53	23.28	158.85	139.45	116.70	10.12	605.46

Table 3. Total mass of material categories in one typical multi-family house building built from 1971—1990 (in tonnes)

	1971—1980				1981—1990			
	E3	E4	E5	E6	F3	F4	F5	F6
Minerals	1,303.71	2,567.78	1,658.12	5,514.47	3,816.81	2,475.57	2,934.92	6,272.39
Non-minerals	476.68	170.45	71.963	1,008.65	89.96	63.81	48.88	444.90
Metals	52.95	73.90	155.43	178.46	361.27	144.88	122.29	674.96

The tables demonstrate that the quantity of all materials in single-family and multi-family house building types increased with time and peaked after the 1970s. The majority of all building types were constructed using mineral materials. When individual building types in all periods are compared, it can be seen that multi-family house buildings consume much more material. For instance, the mass of single-family house buildings ranged from 200.9 to 539.4 tonnes. Free-standing single-family house buildings, which form the majority of residential building stock, have 366.19 tonnes of material on average.

On the other hand, with an average of 6.6 thousand t, high-rise buildings were significant contributors to multi-family house buildings. Except for the final period, other multi-family house building types averaged around 1.8 thousand tonnes of material. However, these values will significantly change for the benefit of single-family house buildings when quantities of material are multiplied by the number of buildings per district.

The other important parameters that were calculated are the material intensity coefficients per building type, which are expressed in tonnes per m^2 of the buildings' gross area and presented in Table 4. In the mineral material category, these

Table 4. Average material intensity coefficients per building type (expressed in tonnes per m^2)

Building type		Mineral	Non-mineral	Metals
Single-family house buildings				
1946—1960	C1	2.54	0.10	0.001
	C2	2.00	0.09	0.0003
1961—1970	D1	2.08	0.07	0.02
	D2	1.78	0.12	0.00
1971—1980	E1	2.15	0.02	0.02
	E2	1.38	0.05	0.02
1981—1990	F1	1.88	0.03	0.02
	F2	1.48	0.02	0.02
Multi-family house buildings				
1946—1960	C3	1.81	0.04	0.04
	C4	1.28	0.03	0.002
	C5	1.27	0.03	0.02
	C6	1.20	0.09	0.04
1961—1970	D3	1.19	0.04	0.08
	D4	0.81	0.05	0.07
	D5	1.11	0.05	0.01
	D6	1.15	0.11	0.12
1971—1980	E3	1.07	0.39	0.04
	E4	0.71	0.05	0.02
	E5	1.16	0.05	0.11
	E6	0.74	0.14	0.02
1981—1990	F3	1.37	0.03	0.13
	F4	1.31	0.03	0.08
	F5	1.69	0.03	0.07
	F6	0.97	0.07	0.10

coefficients decreased over time, ranging from 2.54 tonnes per m^2 (1946—1960) to 1.38 tones per m^2 (1971—1980) for single-family house buildings, indicating that the population opted for larger houses. Similar patterns can be seen in multi-family house buildings. Depending on the building types, the material intensity coefficients for minerals ranged from 1.81 (1946—1960) to 0.71 (1961—1970) tonnes per m^2.

Both non-mineral and metal numbers have negligible values in contrast to mineral material categories, but when multiplied by the number of buildings within a district, they may constitute a valuable source of secondary raw materials. Figure 1 shows the number of single and multi-family house buildings per district in Serbia. These numbers were based on the Census 2011 data on dwellings per building type and period of construction, provided by districts [34], and the National Typology data on the number of buildings per building type, provided for Serbia in total [29]. In other words, the National Typology's total number of buildings per building type was multiplied by the share of building types in each district to get the number of building types in each district. As mentioned before, the number of single-family house buildings, both in total values and values for districts, is significantly higher than the number of multi-family house buildings. This implies that all the renovation and/or demolition strategies that local or regional governments may adopt in forthcoming years should be directed to their owners. And in an effort to achieve a more sustainable built environment, their owners may be one of the key game-changers.

In addition, Figure 2 shows the regional distribution of three major material categories embedded in the entire residential building stock constructed between 1946 and 1990. The figure shows that the quantity of materials varies with the degree of economic development in a district. In all three material categories, the Belgrade district, the capital of Serbia and the largest city, has the highest quantities of materials embedded (89.6, 4.1, and 3.2 million tonnes for mineral, non-mineral, and metal material categories, respectively). It is followed by the Južnobačka, Mačvanska, and Nišavska districts, but with far lesser contributions (33 million tonne on average for the mineral material category). These are the districts that, in the process of further urbanisation, may grasp and exploit the full potential of these materials.

On the other hand, the lowest quantities of these materials are found in the Toplička, Pirotska, and Zaječarska districts. The mineral component of the material embedded in their residential building stock varied from 9.6 to 12.2 million tonnes. Combined with a lower degree of economic development and a higher degree of internal migration from these regions, these values imply that the local governments should carefully consider the viability of their waste management and circular economy strategies.

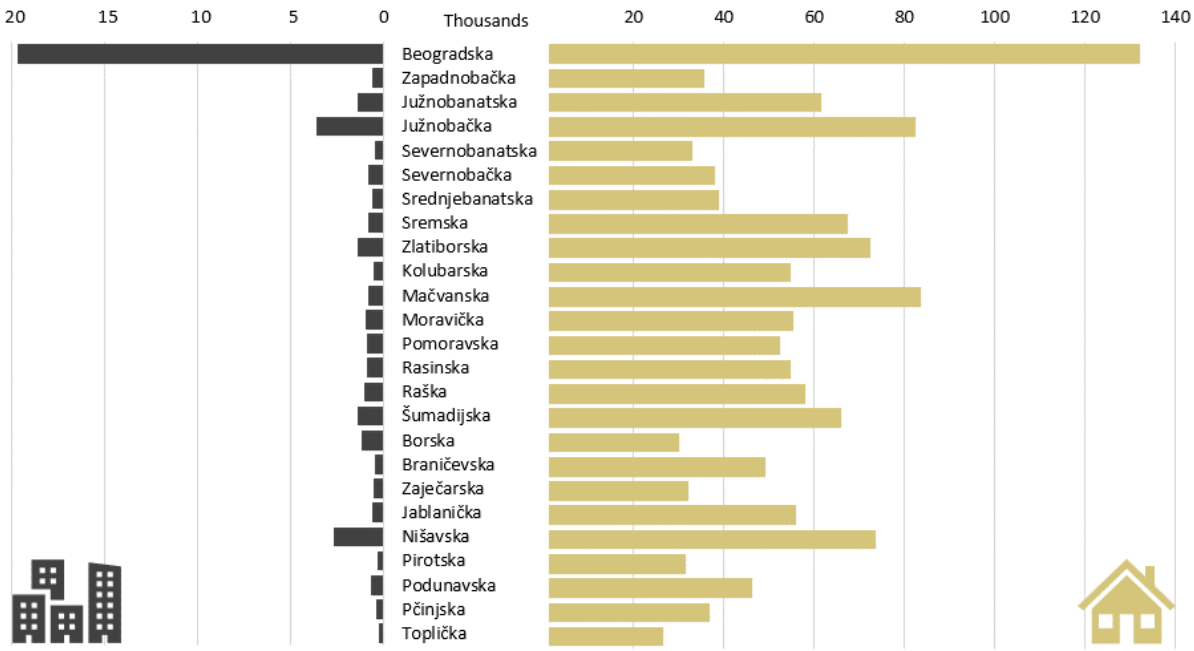

Figure 1. Number of buildings per district: multi-family house buildings (left) and single-family house buildings (right)

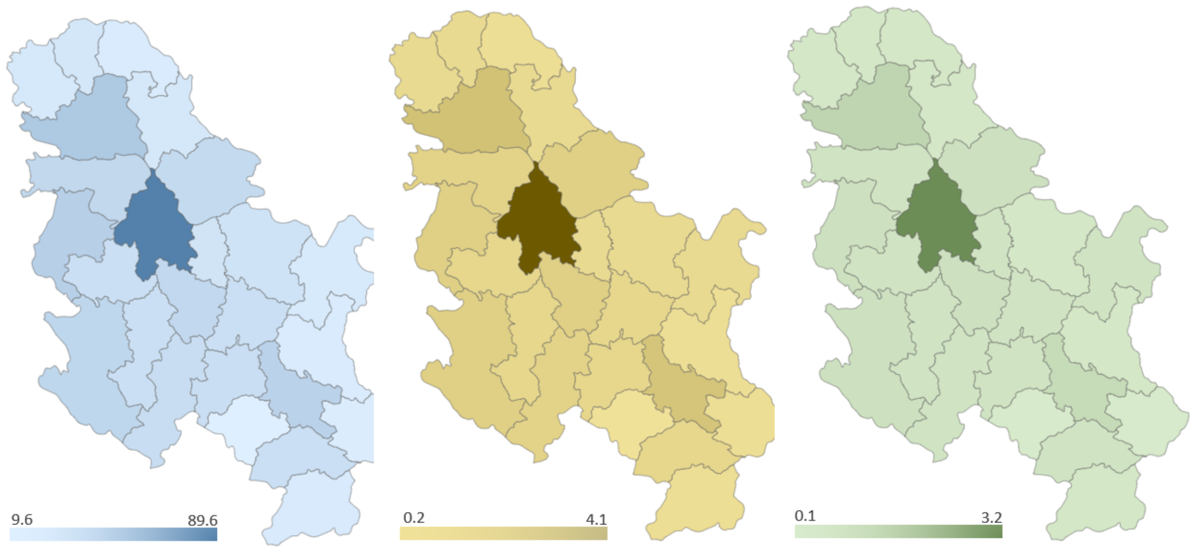

Figure 2. Quantity of material categories per district: minerals (left), non-minerals (centre), metals (right) (in million tonnes)

* *Note: Kosovo and Metohija's districts were not depicted on the map since there was no information on the quantity of buildings and building typologies*

4 Conclusion

In the recent decade, academia and practitioners have been trying to develop efficient and viable waste management and circular economy strategies. To that extent, many studies have been conducted to tackle two challenges: to estimate the amount of material within the economy or assess the sustainability of its treatment options before or when these materials become waste. This study focused on the first challenge and the calculation of the construction material embedded in residential buildings. To overcome this challenge, a methodology for the estimation of material content and quantity is proposed. In addition, to facilitate their use the formulation of regional waste management and circular economy strategies, the materials are grouped into three categories: mineral, non-mineral, and metal. The methodology included a bottom-up inventory analysis, which used the information from the National Typology, i.e., the location and geometry of building elements and the material type from which they are made, and calculated their volumes and weights.

These results were then aggregated, multiplied by the quantity of buildings, and regionally distributed for the entire residential building stock in Serbia constructed between 1946 and 1990. The result showed that the largest number of buildings belongs to single-family free-standing house buildings and that the mineral material category is the highest contributor to the material stock. This suggests that any efficient renovation or demolition strategy should target these buildings and materials. Apart from the formulation of waste and energy efficiency-related strategies, the results also provide a robust base for further modeling of or validation of material intensity coefficients obtained in other ways or in different case studies. These results may also be used for building stock modeling and waste estimations from future renovation and demolition activities.

Future research might include a deeper analysis of mineral material composition to estimate the amount and the treatment potential of reusable components to support the greater implementation of circular economy principles in the built environment.

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