URBAN MINING – POTENTIALS AND LIMITATIONS FOR A CIRCULAR ECONOMY IN THE BUILDING SECTOR

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ABSTRACT

Buildings constitute a major contributor to material use and accumulation in human settlements. Therefore, they play an important role when moving towards a sustainable use of resources. Knowledge about the materials hidden in buildings and the dynamics of the building stock are considered a prerequisite for defining effective resource management measures. In the paper at hand, material quantities present in the urban building stock – using the city of Vienna as a case study – are presented and the potentials and limitations for the recovery and utilization of these materials are discussed. The results of the study indicate that even in a rather “old” city like Vienna, only about 0.3% (or 600 kg/cap/yr) of the overall material stock embedded in buildings (210 Mg/cap) arises as demolition waste and hence is available for material recovery. In contrast, the annual material consumption for the construction of new building amounts to about 1,600 kg/cap/yr. Thus, even a theoretical recycling of demolition waste at a rate of 100% and its sole utilization in the building sector could only substitute for about 35% of primary raw material demand. Moreover, as the material composition of demolished buildings is quite different from currently constructed buildings and because materials derived from demolition waste only meet quality criteria for construction materials with difficulty, further limitations to closed loop recycling of demolition waste exist. Hence, the practical reduction potential for primary raw materials achievable by urban mining of buildings is well below 20%.

Introduction

Based on volume, construction and demolition waste (CDW) is the largest waste stream in the EU (European Comission, 2017). It is estimated that each year about 800 million tons of CDW are generated in the EU-28 (European Commission, 2016). At the same time, the construction sector demands huge amounts of primary resources each year. The annual consumption figures of the EU for sand and gravel (raw aggregates) alone are estimated to be 2.7 billion tons (European Aggregates Association, 2017).

In order to be able to close material cycles in the building sector, profound knowledge of materials usage, on the one hand, and materials entering the waste management system, on the other, is necessary. Whereas detailed knowledge about waste streams is necessary to be able to e.g. achieve EU recycling targets set by the European Parliament and Council of the European Union (2008) for a Circular Economy, it is also important to know about the demand for materials for constructing new

buildings.
In the Circular Economy Action Plan (European Comission, 2017) the recycling of material within the construction sector is encouraged. However, it is unclear to what extent recycled materials can contribute to overall demand and whether circularity is realistic in this sector. Fellner et al. (2017) emphasized the potential contribution of a circular economy as a whole. They stated that the EU´s material stock is still increasing at a significant rate, meaning that material inputs into the economy are much larger than outputs. For a circular economy this implies an inherent limitation to the substitution of primary raw materials by means of secondary ones.
Studies on CDW generation and related secondary raw material availability are frequent, usually focusing on nations or on regions. Hashimoto et al. (2009) looked at construction minerals in Japan as well as related waste accumulation within the society. Bergsdal et al. (2007) projected the CDW generation in Norway based on assumptions on activities in the construction and demolition industry. De Melo et al. (2011) assessed management options for CDW in the Lisbon Metropolitan Area, and based their quantification of CWD generation on construction and transport activity. Solís-Guzmán et al. (2009) based their estimation of CDW in Spain on waste quantities derived from the bills of 100 residential projects investigated. Huang et al. (2013) carried out an MFA-based (Material Flow Analysis) investigation on the material demand and the environmental impact of construction in China, which also covered solid waste generation.
Quantifications of waste materials and modelling approaches aiming at projections have been demonstrated in various studies, yet direct comparisons of the input and output of specific materials to and from the building stock are rare. However, to be able to close material loops and effectively work towards a circular economy, this comparison is crucial.

Hence, the present work aims

- to compare the amount and composition of waste arising from building demolition (output) with materials used for constructing new buildings (inputs) at a regional level,
- to describe recycling and disposal paths of DW in order to illustrate current resource management practice, and
- to discuss possibilities for enhancing resource management practices in the sense of a Circular Economy in the construction sector of the region investigated.

As a case study region, the city of Vienna and its direct surroundings has been chosen.

Material and Methods

The direct comparison between materials available for recycling derived from building demolition waste with materials needed for constructing new buildings requires good data at a regional level. In recent years a number of studies (summarized in Kleemann, 2016) have been carried out in order to better understand the materiality and dynamics of the Viennese building stock. Some of the results of these studies serve as a basis for this research. The relevant data sources used in this research are described in the following subsections.

Specific material intensities for different building categories

In Kleemann et al. (2017a) specific material intensities for different building categories in Vienna were derived from various sources such as detailed investigation of case studies (Kleemann et al., 2016), construction plans of new and demolished buildings, Life Cycle Assessment (LCA) data of new buildings, final bills, and literature. This data has been continuously expanded, and is also used in this study to estimate (i) the materiality of the waste generated through demolition and (ii) the material input to the building stock through new construction activities. Table 2 shows the specific material intensities for different building categories used in this study. All buildings in Vienna were categorized based on Geographic Information System (GIS) data that were collected from different municipal authorities of Vienna and analysed in order to generate a consistent data set with information about size, utilization and the construction period of each building. Combining the GIS data with the materiality of the building categories allowed all building materials to be mapped in a material cadastre.

Demolition activity and associated waste streams

This material cadastre has been used to estimate the amount and quality of waste generated through building demolition in Vienna. In Kleemann et al. (2017b) image matching based change detection is used to quantify the demolished building volume for a one year period. The method applied provides accurate information on the demolition activity by utilizing aerial images of the city. Combined with specific material intensities of the demolished building categories, the DW generation can be assessed. Table 1 shows the amount and composition of the DW generated per person for the reference year 2013. With currently about 1.8 million inhabitants in Vienna, this amounts to a total waste quantity from building demolition of around 1.1 million tonnes per year.

Table 1 Waste arising from building demolition – reference year 2013 (values given in kg per person and year and rounded to two significant digits) (based on Kleemann et al., 2017b)

Material output from buildings in Vienna [kg/cap/yr]					
Mineral	**570**	**Organic**	**15**	**Metal**	**12**
Concrete	280	Wood	11	Iron/Steel	12
Bricks	180	Asphalt	1.4	Aluminium	0.26
Mortar/plaster	77	Bitumen	1.3	Copper	0.15
Mineral fill	15	Various plastics	0.34		
Natural stone	6.0	PVC	0.27		
Slag fill	5.0	Reed	0.25		
Plaster boards/gypsum	2.9	Carpet	0.19		
Gravel/sand	2.6	Polystyrene	0.11		
Foamed clay bricks	1.2	Paper/Cardboard	0.045		
Ceramics	0.86	Linoleum	0.037		
Glass	0.65	Laminate	0.032		
Mineral wool	0.33				
(Cement) asbestos	0.078			Total	600

Table 2 Specific material intensities (given in kg/m³ gross volume) of different building categories in Vienna (values given as medians and rounded to two significant digits) - (based on Kleemann et al., 2017a).

	-1918			1919-1945			1946-1976			1977-1996			1997-		
Material [kg/m³ BRI]	**residential**	**commercial**	**industrial**	**residential**	**commercial**	**industrial**	**residential**	**commercial**	**industrial**	**residential**	**commercial**	**industrial**	**residential**	**commercial**	**industrial**
Mineral	**390**	**430**	**280**	**410**	**340**	**320**	**430**	**350**	**340**	**430**	**380**	**170**	**380**	**320**	**290**
Concrete	22	23	48	100	120	110	240	270	250	300	350	150	360	310	270,00
Gravel/sand				5,8			10			28	2,4		4,3		
Bricks	220	270	170	180	220	180	150	170	31	100	12	9	58	6,1	24
Mortar/plaster	92	81	52	93	73	29	72	44	51	50	16	3,6	3,8	7,5	5
Mineral fill	33	33		33	33		4,9	2,3		14			4,9		1,6
Slag fill	14			5,6			3,7			24					
Foamed clay bricks		0,6	0,38	16		0,38	2,6								
Plaster boards/gypsum	0,15	1,4		0,15	0,17		0,15	7,4		0,82	4,2		9,3	3	4,1
Glass	0,26	0,32	0,68	0,49	0,49	0,27	0,54	0,58		0,55	0,86		0,9	0,62	0,51
Ceramics	0,47	0,54	0,092	0,58	0,47		2	0,9		1,8	0,81		0,092	0,34	0,14
Natural stone	0,017	0,017	46	0,017	2,1		1	1,6		0,78	2,8	7,2	0,47	0,63	2,8
Mineral wool	0,017	0,21	0,016	0,017	0,14		0,62	0,55		1,3	0,32		1,3	1,2	0,83
Mineral wool boards		0,053	0,047			0,047	0,084	0,33							
(Cement) asbestos	0,28	0,13	0,14	1,9		0,14	1,8	0,046		1,6	0,0057				
Organic	**19**	**3,7**	**5,8**	**13**	**7,1**	**28**	**6,5**	**7,6**	**7,6**	**6,7**	**1**	**1**	**8,3**	**5,7**	**5**
Wood	18	3,3	5,8	13	6,6	28	5,9	3,6	3,6	5,4	1,2	1,2	4,3	0,84	2,1
Heraklit	0,27	0,065		0,99	0,065		0,82	0,065	0,065	0,42			0,068		0,023
Paper/Cardboard				0,22			0,2			0,67			0,056		0,019
PVC	0,2	0,17	0,0072	0,1		0,0072	0,52	0,27	0,27		0,12	0,12		0,18	0,1
Various plastics	0,34	0,13	0,069	0,34	0,35		0,85	0,13	0,13	0,94	0,11	0,11	1,1	0,84	0,68
Carpet				1,1			1,1			1,2			0,057		0,019
Laminate							0,33								
Linoleum	0,04	0,04		0,04	0,04		0,03	0,045	0,045	0,01			0,046		0,015
Asphalt								3,7	3,7				5,2		1,7
Bitumen	0,023	0,058	0,14	0,023	0,023	0,14	0,11	2,7	2,7	0,2	0,63	0,63	1,7	2,4	1,6
Polystyrene			0,0028			0,0028	0,23	0,18	0,18	0,18			1,6	0,38	0,66
Metal	**2,8**	**4,30**	**8,80**	**4,6**	**6,00**	**5,80**	**7**	**5,7**	**13**	**6,8**	**13**	**15,00**	**15**	**10**	**13,00**
Iron/Steel	2,7	4,1	8,7	4,6	6	5,8	6,9	5,7	12	6,7	13	14	15	9,5	13
Aluminium	0,019	0,051	0,031	0,019	0,12	0,028	0,033	0,12	0,12	0,14	0,54	0,54	0,15	0,22	0,3
Copper	0,063	0,071	0,0076	0,063	0,092	0,031	0,026	0,067	0,16	0,028	0,2	0,18	0,026	0,029	0,078
Total	**410**	**440**	**290**	**430**	**360**	**350**	**450**	**360**	**350**	**460**	**400**	**180**	**410**	**340**	**310**

Demolition activity and associated waste streams

Data on construction activity is obtained from the municipal building authority (MA 37, 2013) and analysed with respect to the yearly addition of building volume to the building stock. For the analysis, data of a six-year period (2008 – 2013) is used in order to assess the average annual demand for construction materials. As the original data set only provides information on the gross floor area [m²], an average floor height of 3 meters is assumed in order to calculate the gross volume constructed [m³]. Regarding the utilization of new buildings (residential, commercial, industrial), the distribution of the present building stock erected "after 1997" is assumed (54% - residential, 35% - commercial, 6% - industrial, 5% N/A).

Waste management practices

Knowledge about current waste management practice in the demolition sector in the region of Vienna has been gathered by means of knowledge exchange with stakeholders from various municipal authorities, project developers as well as construction-, wrecking- and recycling companies. This knowledge about regional practices is important to assess the status quo and to subsequently identify potentials for improving the current practice towards a more cyclic use of resources.

After quantifying all material flows, the most relevant construction materials are chosen for further discussion. In terms of mass, the most relevant materials are concrete, bricks and mortar. However, less dominant materials such as gypsum, mineral wool or various plastics are also important as they are extensively used in today's buildings and will therefore be relevant for future-oriented waste management strategies. Metals are especially relevant because of their value.

In total 98% of the input and 95% of the output material flows have been analysed with respect to current and potential future management.

Results and discussion

A first number that can be drawn from the comparison between input (2.9 million tonnes) and output (1.1 million tonnes) is the difference of overall material mass entering and leaving the building stock (1.8 million tonnes of annual stock accumulation). Looking at the sole material amounts, one could conclude that around 35% of the material for new construction (input) could be substituted for by means of secondary raw material (output). Assuming a substitution rate this high, however, has a few practical implications as the quality (composition) of the flows is neglected. In order to provide evidence on the "real" resource potential, recycling and disposal paths of certain materials have to be taken into account separately, and are discussed below. In this study, focus is laid on materials assumed to be most important with regard to either mass, value or relevance for waste management. The materials discussed in the following subsections as well as associated quantities are summarized in Table 3.

Concrete

Concrete is the dominant material both in today's construction industry and DW management. When comparing input and output streams of this material, it is clear that only a relatively small share of the material used for new buildings could be substituted for by means of secondary raw material. After demolition, the material is usually transported to outside of the city for processing and recycling since restrictions with regard to noise and dust limit the use of on-site solutions (mobile recycling plants).

The aggregate produced can substitute natural aggregate. Currently it is mainly used as a substructure in road construction. Close to 100% of the concrete is recycled this way. The substitution of aggregate for concrete in construction (e.g. in the Viennese building stock) has, unlike in many other countries, not been implemented yet. The city of Zurich e.g. demands that for newly constructed municipal buildings 50% of the aggregate used in concrete for construction has to be recycled aggregate (Gugerli, 2009). These numbers suggest that all demolition waste in Vienna could be recycled in a closed loop (within the building stock). With regard to environmental impacts, it is important to mention that the cement (which cannot be substituted for by means of concrete debris) is by far the most relevant raw material.

Table 3 **Comparison of materials used in newly constructed buildings and waste amounts generated from building demolition (values are given in tons per year and are rounded)**

Material	Output via demolition waste	Input via demand of construction materials	Difference	"Maximum"[1)] Substitution rate
unit	*[Mg/yr]*	*[Mg/yr]*	*[Mg/yr]*	*[%]*
Concrete	500,000	2,300,000	-1,800,000	21
Bricks	330,000	260,000	75,000	130
Mortar/plaster	140,000	36,000	100,000	380
Gypsum	5,100	46,000	-41,000	11
Glass	1,200	5,400	-4,100	22
(Cement) asbestos	780	0	780	-
Mineral wool	600	8,600	-8,000	7
Wood	20,000	20,000	-27	100
Bitumen	2,400	13000	-11,000	18
Various plastics	610	6800	-6,200	9
Iron/Steel	21,000	89,000	-68,000	24
Aluminium	470	1300	-800	37
Copper	270	210	59	130
Sum of materials considered	1,020,000	2,810,000	-1,790,000	36
Total DW generation/material demand	1,070,000	2,890,000	-1,820,000	37

[1)] *disregarding "quality constraints" for recycling and utilization*

Brick

Brick material is the second largest waste stream in Vienna´s demolition waste and, as shown in Table 3, the amount of output is larger than the input. This would suggest a high substitution potential. However, the material properties of brick make recycling problematic. The burning process of the brick cannot be reversed and the material therefore cannot be reintroduced into brick manufacturing, at least not on an industrial scale. Similar to concrete, the material is processed outside of the city. About 50% of the brick aggregate produced is currently used as a substitute for clay in the cement industry.

The other half is used as substrate for roof greening and gardening purposes. Small fractions (<1%) are used on sport fields or are reused. In general, bricks are well suitable for reuse; however, the demand for old bricks is very limited. At present, the brick industry is quite far away from a circular economy, also due to the inherent material properties of the product. Initiatives in Germany, however, show possibilities for the use of recycled brick aggregate in concrete production and even brick production (Eden and Middendorf, 2009). Due to the high demand for aluminium-oxides and –silicates in the cement industry, a market for brick debris exists in the region of Vienna. Other regions of Austria, however, struggle with limited market possibilities for brick material arising from building demolition.

Mortar /Plaster

The numbers for mortar and plaster show much higher output than input, which is due to the increasing use of concrete, on the one hand, and changing construction techniques of brick walls, on the other. The latter is characterised by a decreasing use of mortar and plaster compared to the buildings being demolished. Mortar and plaster usually arise with brick material and are processed together. During the recycling process, mortar and plaster end up in the fine fraction, of which nearly 100% is landfilled. According to representatives of the recycling industry, there is potential to use the material as a substitute for primary raw material in the cement industry, but this requires continuous quality assurance of the material. Aiming for high quality recycling and controlled processing of demolition waste as well as selective dismantling prior to demolition is therefore crucial. The latter helps to avoid potential contamination of the mineral fractions.

Gypsum

Due to its specific material properties (sound and thermal insulation) and its easy handling, gypsum (in the form of plasterboards) is extensively used in today's interior construction. This has not always been the case, as the large difference in input and output shows. Hence, the substitution potential is relatively low. Examples show that gypsum can be recycled in the plaster board industry in a closed loop (de Guzmán Báez et al., 2015). This would allow a high recycling rate. However, there is no established possibility of recycling gypsum in Vienna and its surroundings, which implies that at present 100% of the material is landfilled. As amounts of gypsum waste are expected to constantly rise in the future, chances are good that recycling will gain a foothold in Austria as well.

Glass

The amount of glass compared to other mineral materials is very low, but the potential for improved recycling is quite high. In most demolition projects, windows and other glass elements are not separately collected and are lost to the mineral fraction. From a technology perspective, recycling of flat glass is possible, but in Austria it is mainly utilized with production waste. In the case of glass, increased recycling seems to be mainly a matter of enforcing regulations (selective deconstruction) and fostering market possibilities.

Cement asbestos

Although the use of asbestos was banned decades ago, diseases related to asbestos exposure are still rising in most countries (Stayner et al., 2013). In particular, when it comes to the renovation or demolition of buildings, this topic is of great importance and will remain so into the future. In Austria, regulations require a non-destructive deconstruction of the material and landfilling in mono-compartments. The case of asbestos shows that some materials need to be safely removed from a circular economy, and underlines the necessity of high quality requirements for new products.

Mineral wool

Mineral wool is used for thermal insulation of the building envelope and in combination with gypsum (plasterboards) for interior construction. At present, there is no possibility to recycle mineral wool in Austria; it is instead co-incinerated in waste to energy plants despite the absent heating value. The main purpose for the thermal treatment of the material is the volume reduction achievable. In general it seems that, similar to gypsum, the quantity of mineral wool is not yet high enough to be problematic for waste management systems. In the future, however, strategies for treating mineral wool waste will become increasingly important (Väntsi and Kärki, 2014). Some types of mineral wool (especially older material) have similar health risks as cement asbestos and require special treatment (non-destructive deconstruction, enclosed transport).

Wood

Wood is an important building material with a long tradition and many utilization possibilities. Numbers in Table 3 suggest a balance between input and output, which indicates decreasing use in relative terms. Whereas wood was used for structural purposes in old Viennese buildings, concrete is taking over this function, especially in larger building projects. In single-family houses, wood still plays a significant role. In Austria about 40% of untreated wood waste is materially recycled in the board industry and about 60% is thermally recovered (Džubur et al., 2017). Planned legislation will probably increase the share of waste wood being materially recycled; however, a closed loop cannot be achieved because treated wood has to be thermally recycled. In this sense, cascading use is a more appropriate term than circular use.

Various plastics

Similarly to gypsum and mineral wool, the use of plastics has been increasing in recent decades and will probably further increase in the future. This development results from requirements on the thermal efficiency of buildings and the use of composite materials. Nowadays most plastic materials (>95%) end up being thermally recycled in Austria. There are a few examples of material recycling (e.g. polyvinyl chloride of window frames), but as with most plastic materials the heterogeneity of polymers and additives make material recycling difficult and sometimes unfavourable (e.g. presence of hazardous additives such as brominated flame-retardants).

Based on the current management of building materials arising from demolition, it can be concluded that in many cases a closed loop is not realized when only the building sector is taken into account. If all construction above and below ground is taken into consideration, one could argue that a circular economy has already largely been established. Only about 150,000 tonnes per year (or 14% of the total

DW) ends up at landfills. Nevertheless, in a strict sense, the “cascading use” of materials might be a more appropriate description than a “circular use” as the quality level in products usually decreases with each re-cycle.

Figure 1 and Figure 2 schematically illustrate the current and the potential future material flows in the Viennese building sector. The material shares of each flow shall be understood as estimates and not as strict values. For simplification in both cases, the resource extraction as an input flow to the production process is assumed to be equal to the construction materials entering the building stock. Hence, ore extractions and therewith associated flows or losses of materials are not considered. Figure 1 shows that the major share of the material is transferred to outside of the building sector (e.g. civil engineering, cement industry, gardening, steel industry, etc.), whereas in Figure 2 increased amounts of material remain in the building sector. The major quantities here concern mineral materials such as concrete and brick being used in concrete for construction, but also reflect assumptions about the recycling of gypsum, glass or mineral wool in the building sector. With respect to the other materials, changes of recycling paths to avoid landfilling and increased material recycling are also assumed. For mortar and plaster it has been used that they are entirely used in the cement industry to substitute for primary material instead of being landfilled. The amount of wood being materially recycled increases from 40% to 60% and bitumen is recycled in road construction. It is clear that such radical changes in the recycling path of a material is unrealistic. In this context, however, these simplifications are accepted in order to highlight potentials for a circular economy in the building sector.

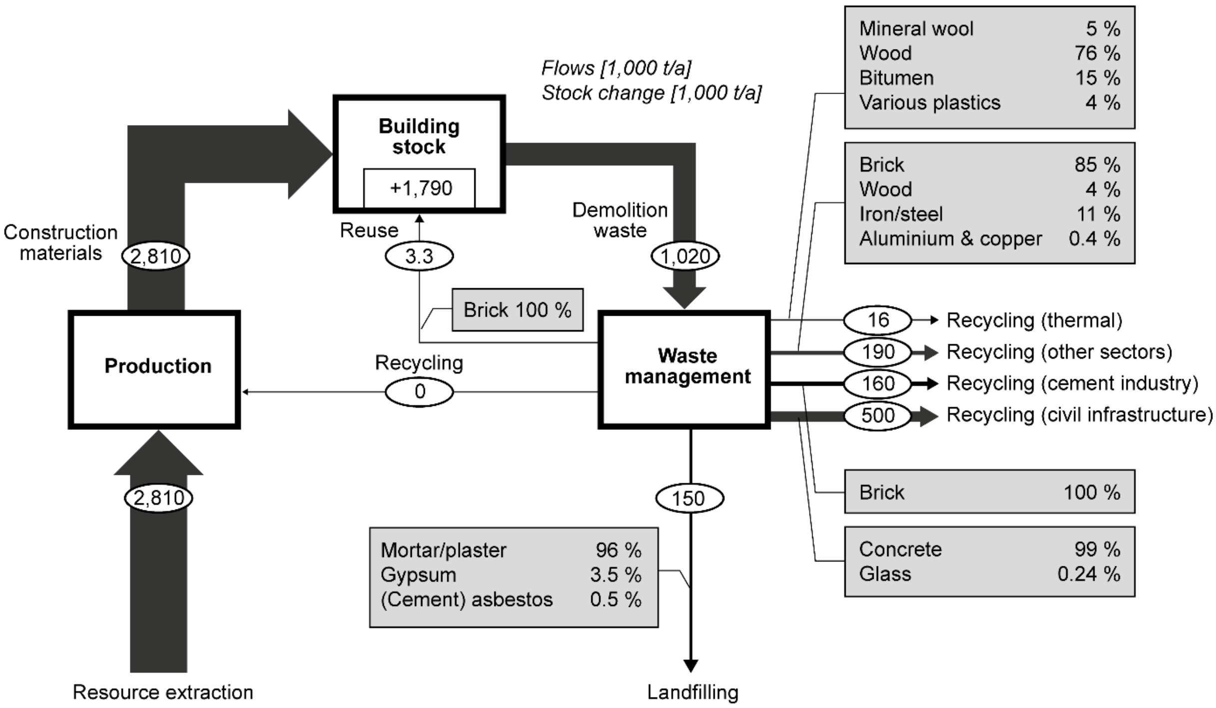

Figure 1 **Schematic illustration of current material flows and recycling/disposal paths of selected materials in the Viennese building sector.**

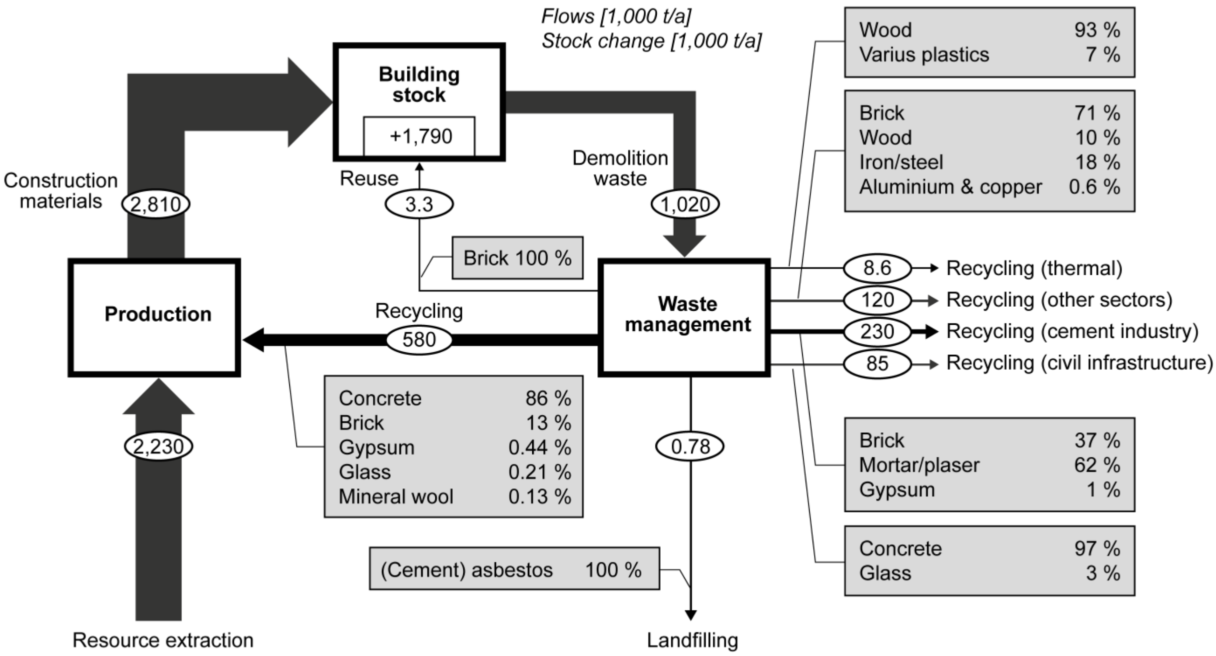

Figure 2 **Schematic illustration of potential future material flows and recycling/disposal paths of selected materials in the Viennese building sector.**

Conclusions:

Based on the results of the study, the following conclusions can be drawn:

- Only a minor share of the total urban building stock (in the present study about 0.3%) becomes annually available for urban mining
- Material stocks in cities are still growing, implying that even a 100% recycling of demolition waste could theoretically substitute for only part of the material demanded by the construction sector (35% for the present case study of Vienna).
- A closed loop recycling of demolition waste (utilization of the materials within the building sector) is difficult to reach as the quality of waste-derived products usually decreases with each re-cycle and the composition of demolished materials do not necessarily meet the current demand of construction materials.
- Cascading use of construction materials is prevailing over circular use.
- Despite various challenges, significant potential for improvement (lower rate of landfilling and higher rate of circularity for demolition waste) exists

Recommendations:

- Additional policy measures, such as quotas for the share of secondary raw materials utilized in construction materials in order to prevent/reduce their cascading use
- Establishing a resource and hazardous substance oriented dismantling of buildings in order to improve the quality of secondary construction materials

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