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Potentials for a circular economy of mineral construction materials and demolition waste in urban areas: a case study from Vienna

Jakob Lederer[a,b,*], Andreas Gassner[a], Fritz Kleemann[a], Johann Fellner[a]

[a] Christian Doppler Laboratory for Anthropogenic Resources, Institute for Water Quality and Resource Management, TU Wien, Karlsplatz 13/226, 1040 Vienna, Austria
[b] Institute of Chemical, Environmental and Bioscience Engineering, TU Wien, Getreidemarkt 9/166-01, 1060 Vienna, Austria

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ABSTRACT

Mineral construction and demolition wastes (CDW) are generated when buildings and infrastructures are renovated and when they reach their end of life. As one of the largest waste streams, they have a considerable potential for the reduction of waste generation, landfilling, and primary raw material consumption. To make use of this potential, sustainable development strategies of many cities include a circular management of CDW by measures in line with the waste hierarchy. The present study uses material flow analysis to determine how waste reduction, re-use and recycling of mineral CDW generated in a city can contribute to reduce the demand of raw material imports for construction minerals, using the case study of the city of Vienna. The results show that the annual consumption of construction minerals of 4.5 million tons can be reduced by 32% to 3 million tons by implementing the waste hierarchy to CDW. The most important measures are the use of recycling materials from mineral construction and demolition waste as recycling aggregate in concrete (575,000 t/yr), followed by the use of recycling material to substitute gravel in unbound form (463,000 t/yr), avoiding the demolition of historical buildings by extending their service life (230,000 t/yr), asphalt recycling (85,000 t/yr), and substitution of raw-mix in cement by recycling material from debris (84,000 t/yr). Re-use of full bricks (17,000 t/yr) is of lesser relevance. To implement this enhanced circularity scenario, however, efforts in installed technology, construction and demolition waste management as well as legal and entrepreneurial measures are required.

1. Introduction

Modern societies consume large amounts of raw materials and produce considerable quantities of wastes, particularly in the construction sector. The main materials consumed and discharged in this sector are minerals (Mayer et al., 2019; Wiedenhofer et al., 2015). Urbanization is one of the main drivers for this development (Kalmykova et al., 2016; Kennedy et al., 2007). For this reason, many cities defined sustainable development targets derived from policies such as the waste hierarchy and the circular economy package (Petit-Boix and Leipold, 2018; Prendeville et al., 2018; Williams, 2019). One main objective of these targets is to reduce the primary raw material consumption, which can be achieved by longer life-times of goods and substitution of primary by secondary raw materials through waste recycling re-use (Gálvez-Martos et al., 2018; Huang et al., 2018; Kuhn et al., 2019). One of these cities is the Austrian capital of Vienna. In its *Smart City Vienna Framework Strategy*, the city defined sustainable development targets in the construction sector. Until the years 2030 and 2050, primary raw material consumption should be stepwise reduced by 30% and 50% respectively. This target is supported by the objective of re-use and recycling of 80% of the materials from demolition activities (City of Vienna, 2019). Furthermore, waste policy in Vienna not only implements the waste hierarchy of waste reduction, re-use, and recycling in order to avoid landfilling, but also foresees a maximum degree of autarchy in waste management to reduce waste exports from the city (Vienna Parliament, 2018b). To define, design, and implement measures towards achieving their sustainability targets in the construction sector, cities like Vienna first need to know the material flows of construction minerals and mineral CDW (Augiseau and Barles, 2017; Pomponi and Moncaster, 2017). There are a number of good examples determining these figures in cities, focusing on the construction minerals demand for residential buildings (Condeixa et al., 2017), transport infrastructure (Guo et al., 2014), and the construction sector as part of the urban metabolism (Hammer and Giljum, 2006; Rosado et al., 2014). A number of studies also investigated CDW generation and recycling (De Melo et al., 2011; Kuhn et al., 2019; Zhao et al., 2010). In order to get a full picture on the quantitative potentials of waste reduction, re-use and recycling to

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* Corresponding author.
E-mail address: jakob.lederer@tuwien.ac.at (J. Lederer).

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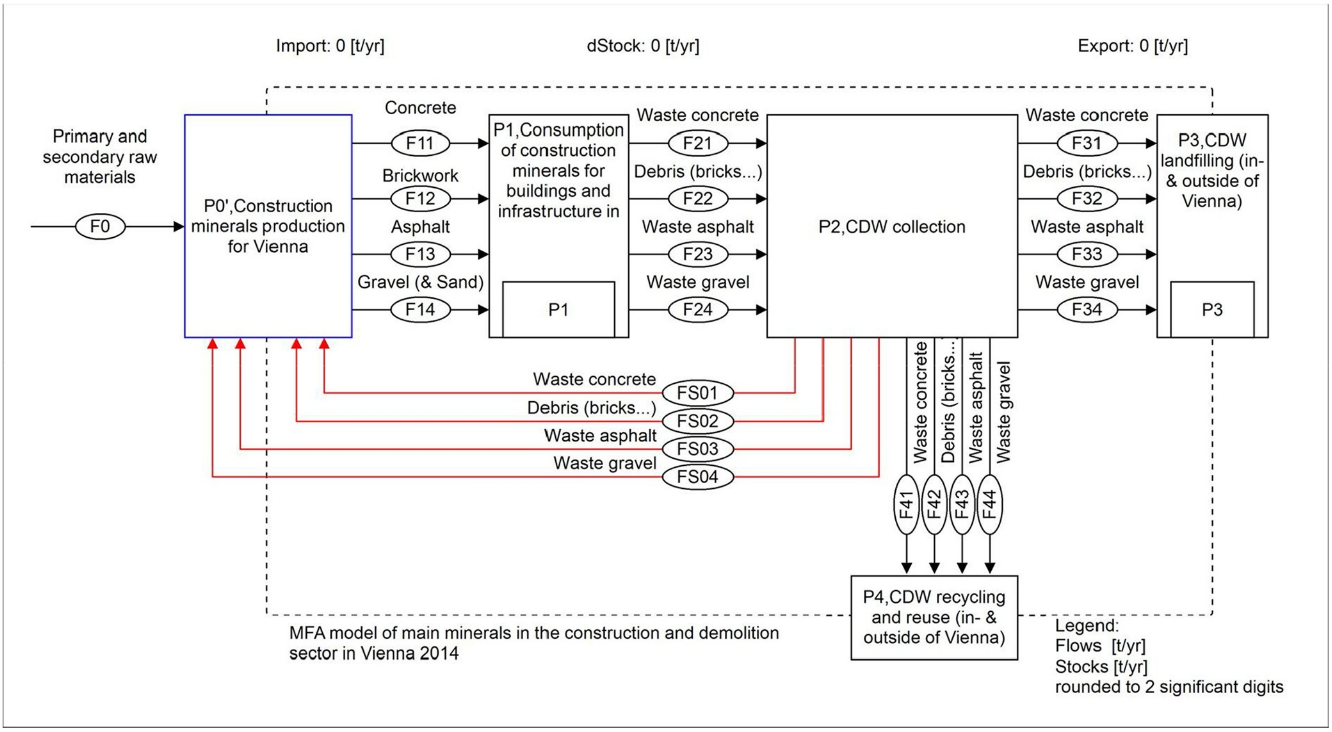

Fig. 1. Model for calculating material flows of construction minerals and mineral CDW in Vienna. The flows FS01-FS04, highlighted in red, are only relevant in the scenario.

mitigate resource consumption and landfilling, however, both, inputs of construction minerals as well as outputs of mineral CDW have to be determined (Kalmykova et al., 2016). Studies like this for cities are available, but only for non-structural construction elements in buildings (Stephan and Athanassiadis, 2018) and not minerals. A detailed study on all mineral construction materials consumed and CDW generated and recycled for a city like Vienna, however, has hitherto not been carried out.

When having established the knowledge on material flows, scenarios towards sustainability in the urban construction sector can be designed. The design of scenarios, however, has to consider a number of factors. Waste reduction by an extension of the life of constructions is challenged by contemporary construction practice and environmental concerns (Hu et al., 2010; Huang et al., 2018; Marique and Rossi, 2018; Wastiels et al., 2016). Re-use in the construction sector is gaining increasing attention, but its quantitative relevance has rarely been investigated (Gálvez-Martos et al., 2018; Nordby et al., 2009). Contrary to that, a lot of literature is available on the qualities and environmental impacts of the use of recycling materials from mineral CDW (Di Maria et al., 2018; Huang et al., 2018; Mália et al., 2013; Rao et al., 2007; Silva et al., 2014). Here, the demand for these recycling materials in the construction sector is an important question to be asked, which is again influenced by legal compliances and construction standards (Hiete et al., 2011; Kuhn et al., 2019; Mahpour, 2018).

From these perspectives, cities like Vienna that aim to reduce the negative impacts of construction minerals use and mineral CDW management, have to ask the following questions:

1. What quantities and types of construction minerals are consumed and mineral CDWs are generated in Vienna, and how are they managed?

2. What is the potential of CDW reduction and recycling to reach higher substitution of construction minerals, and landfill and export less CDW?

These questions also guide the research in this article. Using material flow analysis, first the status quo of construction minerals and mineral CDW management in Vienna is analysed. Then, a circularity scenario is designed that aims to reduce the consumption and thus import of construction minerals in Vienna through different measures. These measures follow the waste hierarchy, but also consider legal and technical restrictions for the use of recycling minerals. Thus, only measures are investigated that have a legal basis and proven technological feasibility in Austria and Europe.

2. Method

2.1. Material flow analysis (MFA)

MFA is a standard method for investigating consumption of construction minerals and mineral CDW management in urban areas Augiseau and Barles, 2017). Based on the law of mass conservation, MFA applies the mass balance and the transfer formula (Equations 1 and 2. These Equations are used to calculate the mass m of unknown material flows F in both, the system under investigation (e.g. a city) as well as in the processes P within this system (e.g. construction minerals production; CDW collection). In the first of these equations, namely

$$\sum_{i=1}^{k} \dot{m}_{input,i} = \sum_{j=1}^{l} \dot{m}_{output,j} \pm \dot{m}_{storage} \tag{1}$$

$\sum_{i=1}^{k} \dot{m}_{input,i}$ is the sum of the mass of k input material flows per time unit, $\sum_{j=1}^{l} \dot{m}_{output,j}$ is the sum of the masses of l output material flow per time unit, and $\dot{m}_{storage}$ is the mass of the material flow into or from a stock located in a process per time unit. The second equation is formulated as

$$TC_j = \dot{m}_{output,j} / \sum_{i=1}^{k} \dot{m}_{input,i} \tag{2}$$

where TC_j is the mass transfer coefficient for an output flow j, $\dot{m}_{output,j}$ is the mass of the output material flow j per time unit, and $\sum_{i=1}^{k} \dot{m}_{input,i}$ is the sum of the masses of k input material flows $\dot{m}_{input}$ per time unit (Brunner and Rechberger, 2016).

2.2. MFA system definition

The MFA is carried out for the status quo and the circularity scenario, shown in Figure 1. All denominations of material flows for the current system *F* (in black) and the scenario *FS* (in red), as well as of processes *P* in the system subsequently used, refer to the model in this Figure. The numbering of the processes is according to their appearance in the article, and the numbering of flows *F* and *FS* indicates first the number of the destination process of the flow, and second the flow number. For instance, flow F23 is the third flow which is destined to process P2. For the illustration of the model and the calculation of the material flows, the MFA software STAN 2.6 was used. Additional calculations were made by Excel.

2.2.1. Construction minerals and mineral CDW fractions considered

The construction minerals considered are the most important in construction, namely concrete, brickwork including mortar and plaster, asphalt, and unbound gravel & sand, termed as gravel (Gassner et al., 2020; Lederer et al., 2020). When demolishing these materials, the CDWs produced are waste concrete, debris (from brickwork), asphalt, and gravel (BMLFUW, 2015).

2.2.2. Temporal system boundary

The temporal system boundary for the MFA was one year. The reference year selected for the status quo and the circularity scenario, was the year 2014, as this was the last year for which a complete data set of construction minerals and mineral CDW was available (BMLFUW, 2015; Gassner et al., 2020; Kleemann et al., 2017a; Kleemann et al., 2017b; Kleemann et al., 2017; Lederer et al., 2020).

2.2.3. Spatial system boundary

The spatial system boundary was the city of Vienna. Only construction minerals consumed and mineral CDWs generated in the city were considered. The processes supplying the construction minerals and handling the CDWs were physically located within and outside of the city boundaries. Thus, they were set in the MFA model on the system boundary (Figure 1).

To perform the calculations, a subsystem was introduced in Process P0 of the MFA model (Figure 2). This was necessary particularly for the scenario, where construction materials production for Vienna was assumed to be based on the use of raw materials imported, as well as secondary raw materials produced in the city. For example, process P5, Brickwork production, assumed to receive material imports of bricks, mortar, and plaster (flow F51), as well as re-used bricks from the city (flow FS51).

3. Data availability and processing

All data and calculation procedures are presented as Excel table and as STAN 2.6 file in the supplementary materials. The numbering of the sheets in the table refer to each subsection in section 3. The data calculated in Excel was inserted in STAN 2.6 through the data explorer by copy-paste. The STAN 2.6 file performed the final calculations by applying Equation 1 and 2 (subsection 2.1) to the inserted data precalculated in Excel.

3.1. Data and calculation of material flows of the status quo

The data to determine the material flows of the status quo came from different sources, described together with the calculation procedures in the subsequent subsections.

3.1.1. Construction minerals production for Vienna – Process P0

P0 receives primary and secondary raw materials (F0) to produce different types of construction minerals used in Vienna (F11-F14). Recycling materials from the city as assumed in the scenario (FS01-FS04) were not explicitly considered, and the only input flow F0 was calculated in STAN 2.6 by applying Equation 1, balancing this input flow by the output flows F11-F14. These output flows are described in the subsequent subsection.

3.1.2. Consumption of construction minerals in Vienna – Process P1

The construction minerals consumption of concrete (F11), brickwork (F12), and gravel (F14) for buildings was taken from Lederer et al. (2020) and Kleemann et al., 2017. Asphalt (F13) was not relevant in buildings. Both sources calculated these figures by multiplying the buildings annually constructed by the material intensities of different materials. The latter came from Kleemann et al., 2017. The construction minerals consumption F11-F14 for transport infrastructure was taken from Gassner et al. (2020), who calculated these figures by multiplying the annually newly constructed or refurbished length or area of each type of infrastructure by specific material intensities given in t/m or t/m^2. By adding the results of both sources, F11-F14 were determined and inserted in the STAN 2.6 MFA model in order to calculate F0 (see supplementary table, sheet 3.1.2).

3.1.3. CDW collection – Process P2

First, data on the input material flows into Process P2, namely flows F21-F24 (waste concrete, debris, asphalt, and gravel) was retrieved from Austrian national waste statistics (BMLFUW, 2015). To calculate the output material flows of Process P2, which were mineral CDW recycled (F41-F44) or landfilled (F31-F34), the transfer function was applied (Equation 2, subsection 2.1). Therefore, TCs for each waste fraction were determined based on average values in Austria (BMLFUW, 2015). These TCs were inserted in the Process P2 in the STAN 2.6 MFA model which calculated the flows F31-F34 and F41-F44. The TCs used and the data to calculate them are shown in Table 1 and in the supplementary materials (sheet 3.1.3).

3.2. Data and calculation of material flows of the circularity scenario

The standard use of recycling materials from mineral CDW in Austria is the unbound application as gravel (BMLFUW, 2015). However, cities have to diversify this use in order to recycle more CDW within their boundaries (Hiete et al., 2011; Kuhn et al., 2019), and such a diversification is assumed in the scenario. Furthermore, the scenario should reflect current available technology and waste legislation, particularly the waste hierarchy of waste reduction, re-use, recycling, and landfilling (Vienna Parliament, 2018b). For these reasons, one reduction (avoidance of building demolition), one re-use (of full bricks), and three recycling options (recycling of asphalt, aggregates in concrete, and debris as clinker raw-mix) of mineral CDW were considered in addition to the use of recycling material as gravel. The denominations of recycling materials from mineral CDW (R_c for concrete, R_b for debris dominated by bricks, R_a for asphalt, R_u for gravel) correspond to Austrian and European standards (ASI, 2018b; Silva et al., 2014) (see Figure 2). The following subsections describe the measures in the scenario.

3.2.1. Reduction of mineral CDW debris generation (F22) and construction minerals demand (F11, F12, F14) by avoided demolition of buildings

The second largest sub-category of buildings demolished in Vienna in the year 2014 were residential and commercial buildings built before the year 1919 (Kleemann et al., 2017). A new paragraph in the construction law that aims to protect the cultural heritage of the city should reduce the number of buildings from this category being demolished (Vienna Parliament, 2018a). For the circularity scenario, it was assumed that this law was strictly enforced, leading to a non-demolition of the buildings in the mentioned building categories. The data to calculate this CDW reduction was taken from Kleemann et al., 2017 who determined the quantities of CDW fractions from residential and commercial buildings constructed before 1919 and demolished in 2014. By

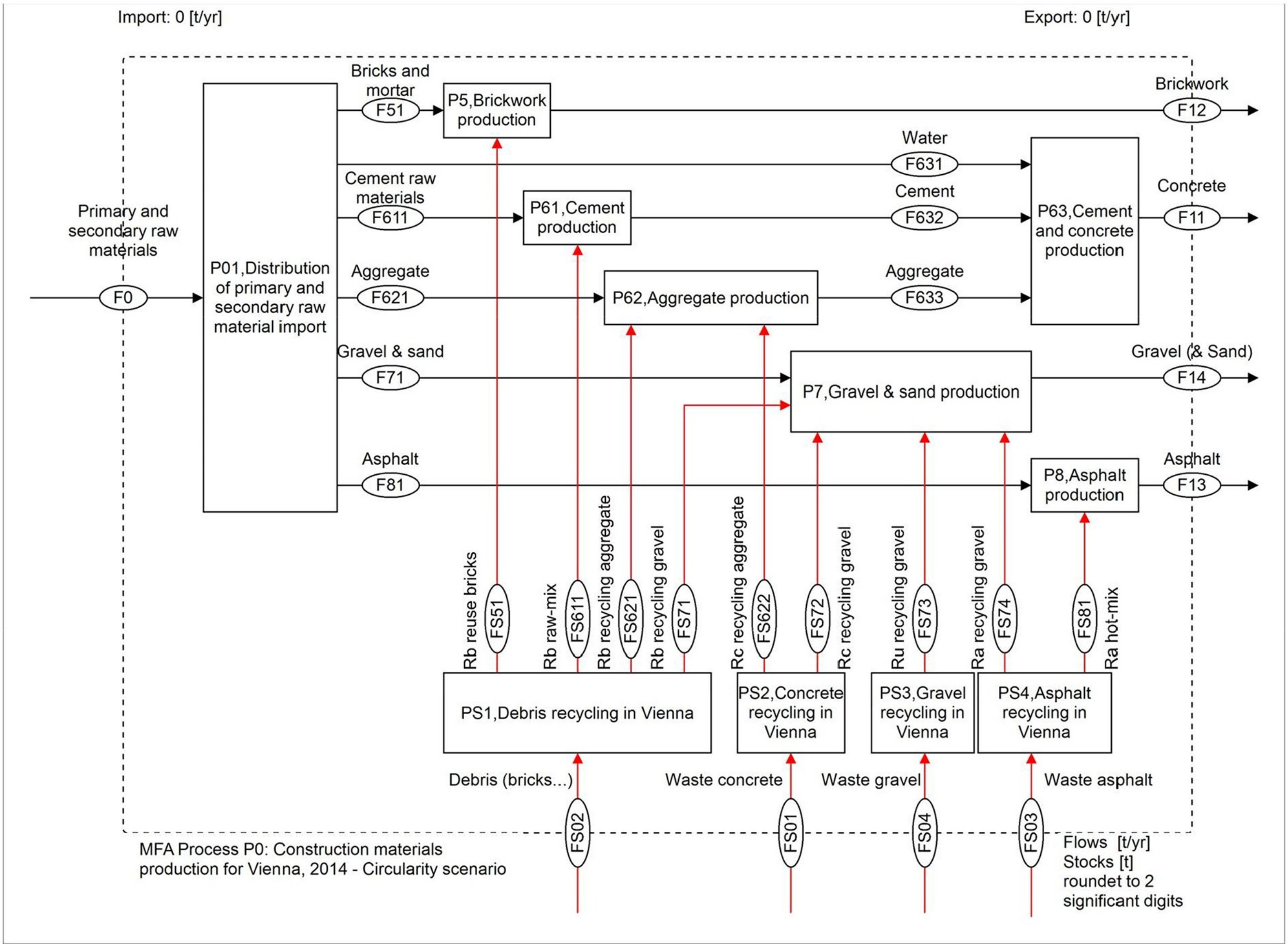

Fig. 2. Model for calculating material flows of the sub-system construction minerals production for Vienna, 2014. The flows FS01-FS81, highlighted in red, are only relevant in the scenario.

subtracting this amount of CDW, which is mainly debris, from CDW debris generated in total, a new value for flow F22 was calculated. The avoidance of buildings demolition also resulted in a reduction of construction minerals used, as demolished buildings were usually replaced by new ones. The thereby avoided construction minerals demand was relevant for concrete (F11), brickwork (F12), and gravel (F14). The reduction in the demand of these construction minerals was calculated by multiplying the gross volume of residential and commercial buildings constructed before 1919 and demolished in 2014 by the material intensities of newly constructed residential and commercial buildings, using data from Kleemann et al., 2017. The resulting avoided construction minerals demand was subtracted from the initial demand as calculated for the status quo (supplementary table, sheet 3.2.1). For all subsequently described re-use and recycling options, the data on construction minerals demand and mineral CDW generation after applying the waste reduction scenario was used.

3.2.2. Re-use of bricks (FS51) from debris (F42) to substitute brickwork (F12)

In Vienna, as in many other cities with a large number of old buildings, bricks are the most important minerals considered for re-use. The supply of these bricks from demolition would be huge, but in practice, they can only be recovered when buildings are dismantled during renovation works, and not demolished, as this would destroy the bricks (Nordby et al., 2009). The most important of these renovation activities in Vienna were attic extensions of buildings built before 1919. The number of these attic extensions was about 400 per year (Gruber et al., 2018). In each of the old attics, the pediment walls and the floor were brick-made and had to be dismantled for the extension. These bricks are usually available for re-use. Using the properties

Table 1
CDW data from different sources in t/yr, and TCs calculated using this data
*Sources: *BMLFUW (2015); **calculated*

Mineral CDW fraction	Concrete	Debris	Asphalt	Gravel	Total
Statistical data for Austria and Vienna [unit]					
CDW generation Vienna [t/yr]* (flows F21-F24)	555,020	806,611	206,978	257,451	1,826,060
CDW generation Austria [t/yr]*	3,491,000	2,731,000	1,634,000	1,103,000	8,959,000
CDW recycling in Austria [t/yr]*	3,480,000	2,292,000	1,615,000	1,082,000	8,469,000
$TC_{\text{CDW generation} \rightarrow \text{landfill Austria}}$ [-]** (to calculate F31-F34)	0.003	0.161	0.012	0.019	
$TC_{\text{CDW generation} \rightarrow \text{recycling Austria}}$[-]** (to calculate F41-F44)	0.997	0.839	0.988	0.981	

(geometry, layer thickness of walls and floors, composition and density of brickwork) of an average residential building constructed before 1919, the total mass of bricks that can be dismantled was estimated. The data to do so was assumed based on Kleemann et al., 2017 and thereafter, a attic extension had an average ground area of 30 by 10 m, a pitch of 45°, a pediment wall height of 5 m, a layer thickness of 0.25 m for the pediment wall and 0.06 m for the floor, a brick share in brickwork of 70%, and a brick density of 2 t/m^3. The thereafter calculated quantity of bricks reclaimed per attic extension was multiplied by the 400 attic extensions per year. This amount, shown in Figure 2 as flow FS51, reduced the demand for primary raw material in brickwork (F12) (supplementary table, sheet 3.2.2).

3.2.3. Recycling of waste asphalt (FS81) to substitute raw materials (F81) in asphalt hot-mix (F13)

Asphalt recycling is state of the art in many countries, including Austria, were about 10% of the asphalt hot-mix contains recycling material from waste asphalt (Heller and Hierzer, 2012; Kranz, 2019). In addition, there are no limitations in the standards for the waste asphalt contents (ASI, 2018a). While studies suggest that a substitution of up to 80% of primary raw materials by recycled asphalt R_a is feasible, a substitution of 40% is an ambitious though likely assumption (Izaks et al., 2015; Pirklbauer, 2015). In the scenario, it was thus assumed that R_a (FS03) was used to substitute 40% of the primary asphalt raw materials (flows FS81) to produce less resource intensive asphalt (F13) (supplementary table, sheet 3.2.3).

3.2.4. Recycling material from waste debris (FS621) and concrete (FS622) to substitute aggregates (F621) in concrete (F11)

The use of recycling aggregate in concrete, even though practiced in many European countries, is a young phenomenon in Austria (Tam et al., 2018). Since the Austrian standard for concrete allows this use, it was considered in the scenario (ASI, 2018b). The amount of aggregate in concrete was calculated based on the concrete consumption (F21, after CDW reduction) multiplied its average content in concrete of 78.7% (IBU, 2018). How many of this aggregate can be subsituted by different recycling minerals, depends on the type of concrete, and four of these were distinguished, based on the Austrian concrete standard (ASI, 2018b) (Table 2).

Concrete 1 is the most widely used concrete in residential and commercial buildings. Compressive strength and exposure class are C30/37 and XC2 or lower. If containing R_b, they can only be used in walls and foundations. In this concrete, 25% of the aggregate mix of coarse and fine aggregates is substitutable by recycling aggregates consisting of less than 30% R_b and more than 50% R_c. The assumed composition of recycling aggregates (30% R_b and 70% R_c) leads to a total aggregate composition of 7.5% R_b, 17.5% R_c, and 75% primary raw materials.

Concrete 2 has a compressive strength of C40/50 and below. It is used in buildings with risk of carbonisation (XC3, XC4), de-icing salt (XD1), freeze and thaw (XF1), and acidic attack (XA1), but also in ceilings of ordinary buildings. In these concretes, only recycling aggregates R_c are allowed. The maximum substitution of primary raw materials is 25% for coarse ($\geq$4 mm), and 50% for fine aggregates ($\leq$4 mm). The diameter-based aggregate composition was assumed as 56% fine and 44% coarse aggregates, and the resulting substitution rate of primary raw materials by R_C was 36%.

Concrete 3 is a concrete with a compressive strength of C40/50 and below, but with a higher resistance against de-icing salt (XD2, XD3) and freeze and thaw attack (XF2, XF3, XF4). These concretes are mainly used in industrial and other buildings. The substitution rate here is 30% for fine and 15% for coarse aggregates. Applying the same grain-size based composition as for concrete 2, the substitution rate of primary by recycling aggregates was 22%.

Concrete 4 is mainly used for roads (XM) and does not allow the use of recycling aggregates.

After having defined the concrete types, their share among the concretes used in Vienna was estimated. Concretes C30/37 and XC2 or lower make 90% of all concretes produced in Germany and supposedly also in Austria (Statista, 2020). As only walls and foundations can contain concrete having these properties, we assume that 50% are of type 1, while 30% are of type 2 (for ceilings). About 10% of concretes used in Vienna are for industrial and other buildings and can thus be assigned to concrete 3 (Lederer et al., 2020). About 10% of concretes were of type 4 used in infrastructure and cannot contain recycling aggregates (Gassner et al., 2020). Table 2 and sheet 3.2.4 in the supplementary file summarize these assumptions.

3.2.5. Recycling of waste debris (FS611) to substitute raw-mix of cement raw materials (F611) in cement (F632) for concrete (F11)

In Austria, up to 10% of the raw-mix for Portland cement clinker production come from mineral CDW debris to supply Aluminium (Al) and Silica (Si) oxides (Lederer et al., 2017; Mauschitz, 2017). Based on experiments, it can be assumed that 20% of the raw-mix can be substituted by recycling material from debris R_b originating from the city (Zeitlhofer et al., 2018). The average concrete used in Vienna contained 13,3% cement (IBU, 2018), and the ratio between the input into integrated cement plants and cement produced is 1.1, which is due to the calcination of limestone (Lederer et al., 2017). Based on that and the total amount of concretes used in Vienna (F11), the cement demand and thus the substitutable primary raw materials for cement by mineral CDW debris generated in Vienna, were calculated (supplementary table, sheet 3.2.5).

3.2.6. Recycling material from waste debris (FS71), concrete (FS72), waste gravel (FS73), and asphalt (FS74) as raw material in infrastructure (F13)

This use of recycling minerals from CDW represents the standard in Austria. There are different applications, but the most important use is in road constructions. In this application, the most relevant requirements to the material used therein are compressive strength, frost resistance, and swelling properties. From these requirements, recycling materials R_c, R_u, and R_a are more suitable than R_b. Thus, in the circularity scenario, the substitution of gravel was assumed first by R_c, R_u, and R_a, and the remaining was assumed to be substituted by R_b (supplementary table, sheet 3.2.6).

3.2.7. Data entry in STAN 2.6 using the data explorer excel interface

To enter the data determined in excel for the status quo (subsection 3.1) and the scenario (subsection 3.2) as shown in the supplementary table, the data explorer in the STAN 2.6 MFA model was opened, and the data for material flows (supplementary table, sheet

Table 2

Share of different concretes used in Vienna for calculating the circularity scenario

Type	Compressive strength	Exposure class	Aggregate composition R_B brick (debris)	R_C concrete	Primary	% of concrete in Vienna
1	≤C30/37	XC0-2	7,5%	17,5%	75%	50%
2	≤C40/50	XC3-4, XD1, XF1, XA1	0%	36%	64%	30%
3	≤C40/50	XD2-3, XF2-4	0%	22%	88%	10%
4	-	other concretes	0%	0%	100%	10%

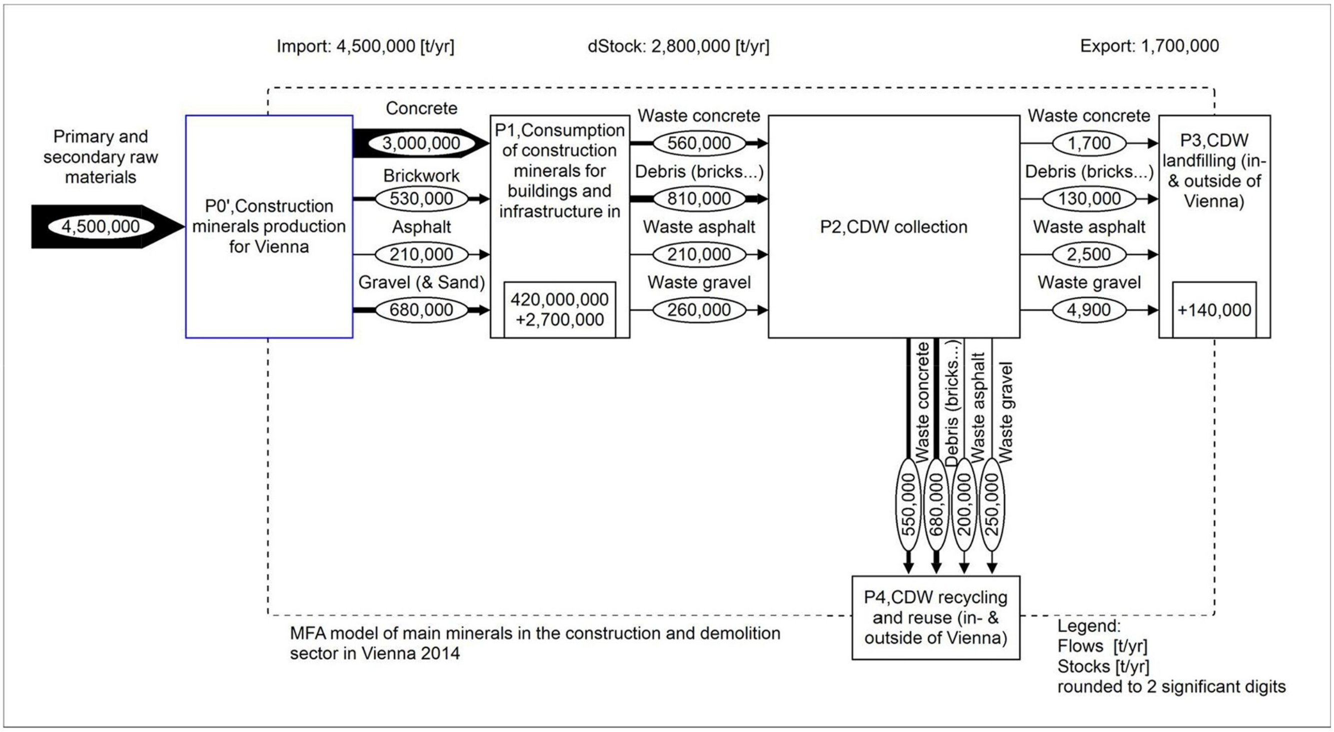

Fig. 3. Material flows of construction minerals and mineral CDW in Vienna, 2014 – status quo

3.3.1) and transfer coefficients (supplementary table, sheet 3.3.2) were inserted by copy-paste.

4. Results and Discussion

4.1. Material flows of mineral construction materials and CDW in Vienna in 2014

Figure 3 and Table 3 show the calculated material flows of construction minerals and mineral CDW in Vienna in 2014, detailly presented and discussed in the subsequent subsections.

4.1.1. Consumption of mineral construction materials

In 2014, Vienna consumed 4.5 million t/yr of construction minerals. 72% of these were used in buildings, and 28% in transport infrastructure. 68% were concretes, 12% brickwork, 5% asphalt, and 15% gravel. The latter divided into a fraction for special engineering purposes (5% or 214,000 t/yr) and ordinary purposes (10% or 445,000 t/yr). The total amount corresponds to 2.5 t/capita/yr, a figure that is lower than for Lisbon (3.2-5.0 t/capita/yr), Vienna in the year 2003 (5.1 t/capita/yr) or Hamburg in the year 2003 (6.0 t/capita/yr) (Hammer and Giljum, 2006; Rosado et al., 2014). A comparison between the figures, however, is difficult for a number of reasons. First, cement had a share of 30% of the total non-metallic minerals consumption in Lisbon, which is an unrealistic high value indicating some data inconsistencies in that study (Rosado et al., 2014). Second, Rosado et al. (2014) and Hammer and Giljum (2006) used a top-down approach based on input-output tables, while this study used a bottom-up approach. The latter tends to underestimate total material flows and stocks (Schiller et al., 2017), but was used in the study at hand to provide a better insight, for instance to determine the share of recycling materials in construction minerals consumed. Based on the data available, however, this was not possible, and the reasons for that are discussed in subsection 4.1.3.

4.1.2. Generation and management of mineral CDW

The in total generated 1.8 million t/yr of mineral CDW in Vienna correspond to 1 t/capita/yr (see Table 3). This value is similar to the Austrian average for the same year, higher than in Lisbon in 2007 (0.6 t/capita/yr), but lower than in the Canton of Zurich (1.8 t/capita/yr), indicating not only different construction practices, but also data availability. For instance the value for Lisbon had to be estimated by the authors (BMLFUW, 2015; De Melo et al., 2011; Kuhn et al., 2019). In Vienna, waste debris was the largest CDW stream (44%), followed by concrete (30%), gravel (14%), and asphalt (11%). This result is in contrast to the input of construction minerals, where concrete dominated. In practice, this means that old brick-buildings were demolished and substituted by concrete buildings. By applying the transfer coefficients for mineral CDW recycling and landfilling from Austria to Vienna, only 8% of mineral CDW was landfilled, while 92% was recovered. As shown in Table 3, this corresponds to in total 1.7 million t/yr of recycling materials produced and 139,000 t/yr of CDW landfilled.

It must be mentioned at this point that these results bear some uncertainties and have to be improved. Vienna is not Austria, and it is

Table 3
Status quo of mineral construction materials consumption and CDW management in Vienna 2014

	Concrete	Brickwork / debris	Asphalt	Gravel & sand	Total
Construction minerals consumed [t/yr]	3,049,655	534,019	213,749	679,054	4,476,477
CDW from Vienna landfilled [t/yr]	1,749	129,660	2,407	4,902	138,717
CDW from Vienna to recycling [t/yr]	553,271	676,951	204,571	252,549	1,687,343
Landfilling rate	0%	16%	1%	2%	8%
Recycling rate	100%	84%	99%	98%	92%

likely that the TCs at city level differ from the national ones, but the data on the share between landfilling and recycling was only published at national and not at provincial level. The second problem is that the data from Austria considered CDW to be recycled when it entered the recycling plant. These plants, however, produce also outputs that were landfilled, and it was not clear whether these outputs were already considered in the CDW landfilling statistics (BMFLUW, 2015). In future, this information should be established.

4.1.3. Circularity of construction minerals supply and CDW management in Vienna

Based on the data available, it was not possible to determine the share of recycling materials from CDW in construction minerals consumed in Vienna, even though it is known that re-use of bricks, recycling of asphalt as hot-mix, and recycling of debris in cement production was practiced (see subsection 4.1.2). The lack of this information is a problem as it does not allow to evaluate the success of policies on waste reduction and recycling. For this study, however, solely the comparison of the recycling materials production (1.7 million t/yr) with the primary raw material that is usually substituted by these materials, namely unbound gravel for ordinary purposes (0.4 million t/yr), it becomes clear that the targeted circularity and autarky cannot be fulfilled in Vienna in 2014. There were simply too many recycling materials available for gravel substitution. The same was experienced by the Canton of Zurich, and led to a shift there from using recycling minerals solely in their unbound form towards recycling them in bound form in concrete or asphalt. Nowadays, 60% of all recycling minerals used in Zurich are recycled in that way (Kuhn et al., 2019). In Vienna where this is not the case, large amounts of recycling minerals had to be exported. This situation, however, can be changed, and the quantitative impact of options to do so are presented in the next subsection.

4.2. Scenario for a more circular management of construction minerals in Vienna

The MFA for the circularity scenario (based on the year 2014) is illustrated in Figure 4. The result shows that in total, 230,000 t/yr of CDW debris can be avoided and of the remaining minerals CDW, in total 1,225,000 t/yr of CDW can be recycled in Vienna, thus reducing raw material imports by 32% (from 4.5 to 3.0 Mio t/yr) and the amount to be landfilled by 28% (from 139,000 to 100,000 t/yr). Furthermore, no export of recycling materials from waste concrete, asphalt, and gravel would be required anymore, while only 270,000 t/yr of recycling materials from CDW debris had to be exported or used for other purposes in the city as discussed in subsection 4.3. Figure 5 and Table 4 show the results in detail.

4.2.1. Reduction of mineral CDW debris generation by avoided demolition of buildings

With a reduction potential of 230,000 t/yr of CDW generation and 214,000 t/yr of construction minerals consumption, avoided demolition of buildings was the quantitatively third most important measure in the scenario. From a qualitative perspective, this measure was even more important, as the waste fraction reduced, namely CDW debris, was also the one with the highest landfilling rate. Furthermore, the main construction mineral were consumption was reduced by the measure was concrete, which has the highest CO_2 footprint of all the construction minerals considered (Di Maria et al., 2018). Vienna has also the legal means to reduce this waste fraction. Even though protection of the cultural heritage and not circularity was the main reason for the new paragraph in the construction law, it stricter regulates the demolishing of old buildings (Vienna Parliament, 2018a). According to this law, authorities decide whether a demolition of such a building takes place, and if not, they unintentionally contribute to a reduction of CDW generation, landfilling, and mineral construction material consumption in Vienna. The multiple effects of this law can be seen as an opportunity to streamline the policy on cultural heritage protection with the sustainability targets by including the raw material consumption and waste reduction aspect in addition to the cultural heritage argument in the decision on building demolishing. However, circularity and reduction of construction minerals consumption is one parameter, greenhouse gas emissions and energy demand along the life cycle of a building another one, and should thus be considered too. New buildings substituting old ones may have a lower life cycle impact, due

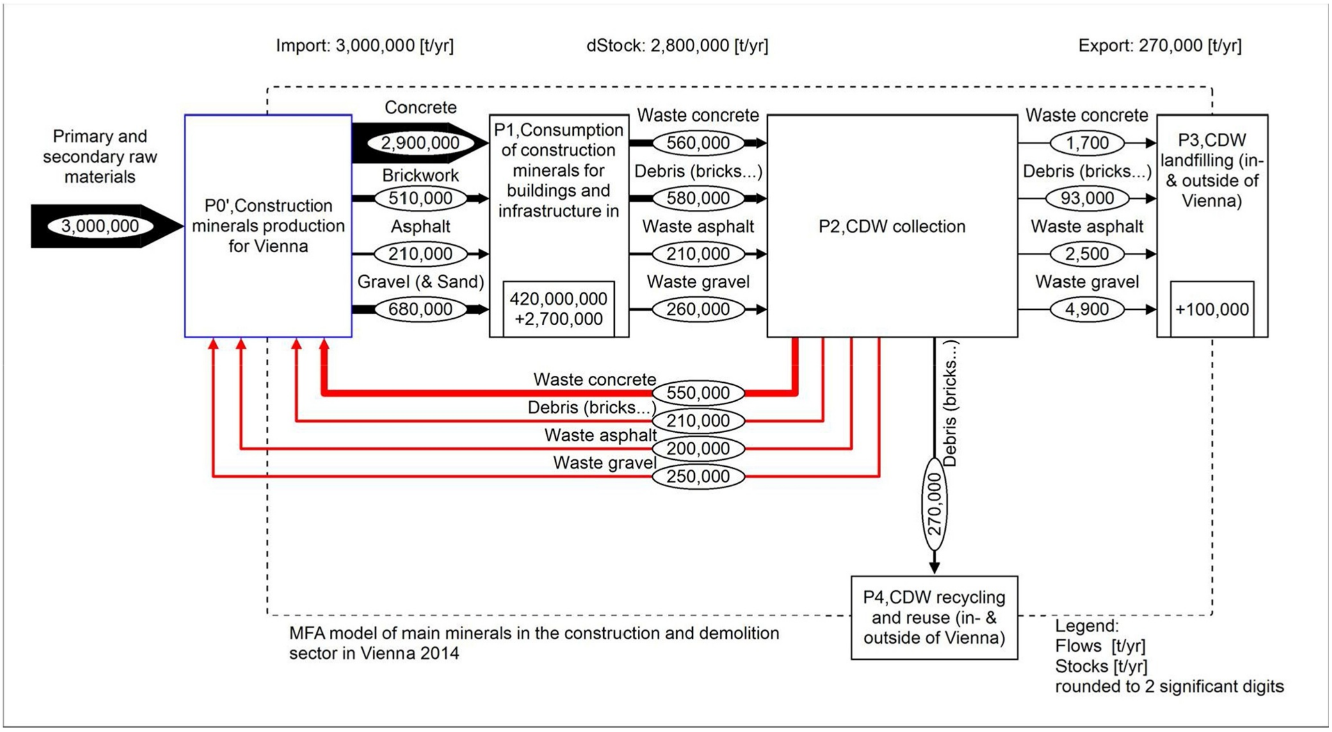

Fig. 4. Material flows of construction minerals and mineral CDW in Vienna 2014 – circularity scenario

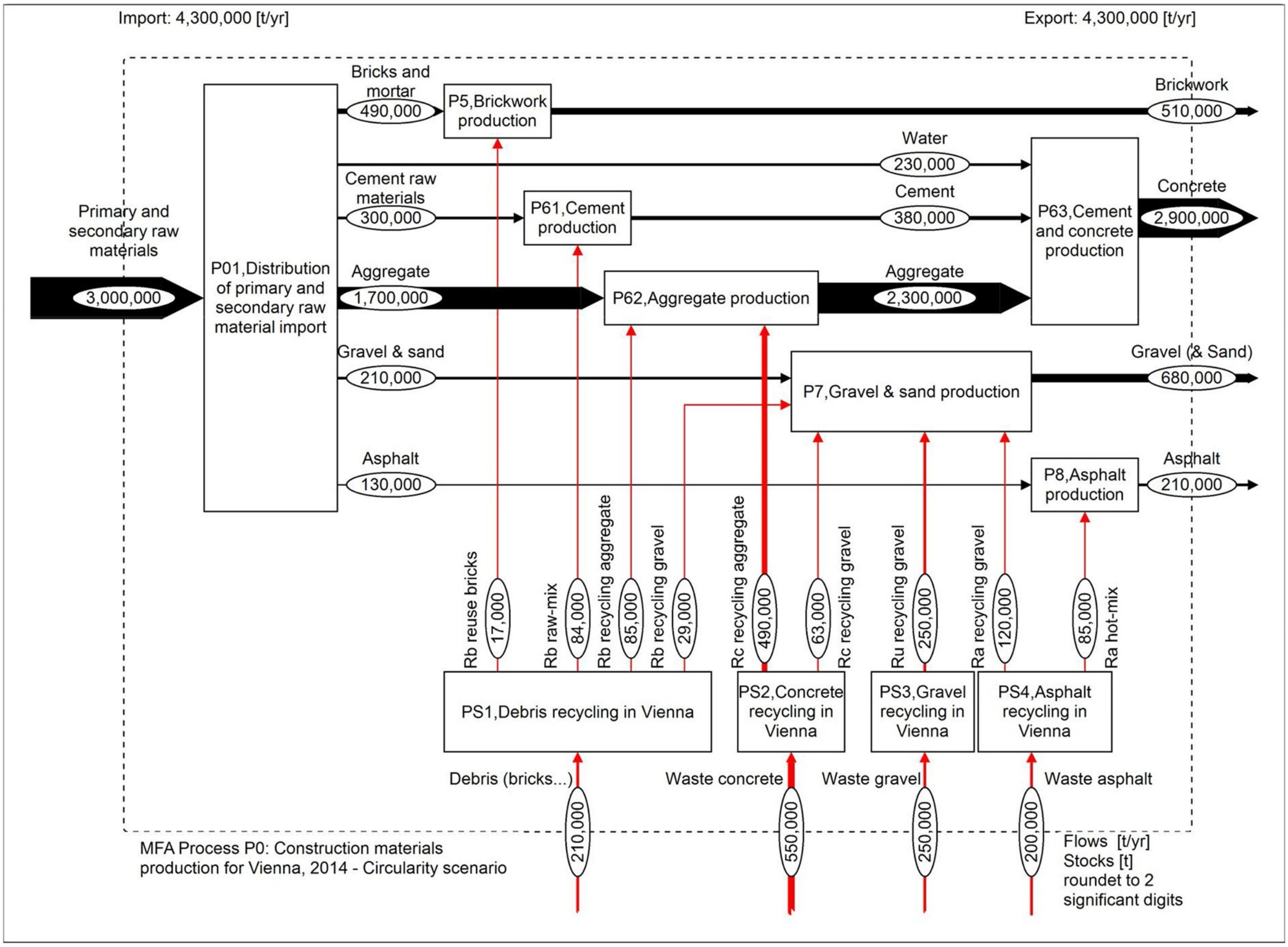

Fig 5. Mineral construction minerals production for Vienna 2014 – circularity scenario

Table 4
Summary of scenario results

Reduction, re-use and recycling scenarios	Subsection	Material flows	Recycling material derived from CDW fraction in t/yr					Share
			Concrete	Brickwork	Asphalt	Gravel	Total	
Reduction of mineral CDW debris	4.2.1	F22		229,979			229,979	15%
Re-use of bricks	4.2.2	FS51		17,080			17,080	1%
Recycling of waste asphalt	4.2.3	FS81			85,499		85,499	6%
Recycling aggregates in concrete	4.2.4	FS621, FS622	490,520	84,572			575,092	39%
Recycling as raw-mix in cement	4.2.5	FS611		84,022			84,022	6%
Recycling as gravel	4.2.6	FS71, FS72, FS73, FS74	62,835	62,835	118,995	252,559	497,225	33%
Summary of scenario results	4.2	FS01, FS02, FS03, FS04	553,355	478,489	204,494	252,559	1,488,897	100%
Impact of scenario on construction minerals consumption		Material flows	Recycling material derived from CDW fraction in t/yr					
			Concrete	Brickwork	Asphalt	Gravel	Total	
Construction minerals demand after avoided demolition	4.2	F11, F12, F14	2,865,646	505,873	213,749	677,174	4,262,441	
Reduction of construction minerals demand by avoided demolition	4.2.1	F11, F12, F14	184,009	28,146	-	1,880	214,036	
Primary and secondary raw material import after scenarios	4.2	F0					3,037,504	
Impact of scenario on CDW landfilling and export		Material flows	Recycling material derived from CDW fraction in t/yr					
			Concrete	Brickwork	Asphalt	Gravel	Total	
Mineral CDW landfilling	4.2	F31-F34	1,665	93,415	2,484	4,892	102,456	
Mineral CDW export	4.2	F42	-	272,275	-	-	272,275	

to the larger number of apartments they usually contain and the lower energy demand for heating. The renovation of old buildings not demolished towards higher energy efficiency and more apartments by attic extensions may lower and even turn this effect. Studies on this topic, however, show quite contradictory results (Marique and Rossi, 2018; Wastiels et al., 2016). Thus, similar studies have to be carried out for different types of old buildings to be demolished and their new substitutes, considering the achievable number of apartments, thermal insulation standards, and the impacts of construction materials supplied and CDW disposed. This would result in a list of criteria upon which authorities can make an informed based decision on the demolition and substitution, or renovation of an old building.

4.2.2. Re-use of bricks from debris to substitute brickwork

Even though ranked second in the waste hierarchy, the lowest potential in the scenario presented to reduce raw material consumption and mineral CDW generation was found for the re-use of bricks. It is even questionable if the low potential of 17,080 t/yr as determined can find its market. The reasons for that are manifold and include the workability as well as the inferior thermal insulation properties of these bricks (Nordby et al., 2009). This limited marketability results in the re-use of bricks for minor construction purposes such as renovating old brickwork or pigeon fancying. However, it also highlights a dilemma of generally reusable goods with a long lifetime: at the time when they are available for re-use, they are out of date, and standard.

4.2.3. Recycling of waste asphalt to substitute raw materials in asphalt hot-mix

With 85,000 t/yr, asphalt recycling has a low absolute quantitative potential for recycling if compared to other measures investigated. However, its potential to reduce the demand on primary raw materials for its parent material fraction, namely asphalt, is with 40% much higher than for other recycling materials, allowing higher substitution rates of primary raw materials in the hot-mix. The main reason for that is that both, aggregate and binder (gravel and bitumen) are recycled. From a future perspective, it is worth to have a look to other countries like Germany or the Netherlands where substitution rates of up to 80% are realized (Izaks et al., 2015). Hence, the potential for asphalt recycling can be even higher than assumed in the scenario and limited by only two factors. The first, which is the presence of hot-mix plants that can achieve a higher substitution rate than 40%, can be solved by both, streamlined tendering by clients (i.e. the public sector) as well as investments in technology by the construction industry. For the latter, these investments are currently on the way in Austria and Vienna (Pirklbauer, 2015). The second factor is rather difficult to solve by technology, namely the presence of PAH contaminated waste asphalts, a problem that led to a decrease of the amount of waste asphalt recycled as hot-mix in Switzerland in the recent years (although from a high level) (Kuhn et al., 2019). To which extend this problem also exist in Austria and Vienna, however, is not entirely clear and has to be further investigated.

4.2.4. Recycling material from waste debris and concrete to substitute aggregates in concrete

With 575,000 t/yr, the largest potential to cover the raw material demand for Vienna by its own recycling minerals, is by recycling aggregates in concrete, consisting of 491,000 t/yr R_c, and 85,000 t/yr R_b. The main reason for this is the large share of concrete in the construction minerals demand in Vienna. Hitherto, and contrary to asphalt recycling and recycling in cement production (subsections 4.2.3 and 4.2.5), this large potential was not used in Vienna. To activate it like in other cities (i.e. Zürich), a number of measures are required (Kuhn et al., 2019). Modern recycling plants for CDW equipped with a washing component in addition to standard processing have to be installed in Vienna (ASI, 2018b). In other parts of Austrian, such plants already exist (Wopfinger, 2019). Furthermore, being the largest client for construction companies in infrastructure and housing, the city of Vienna has the option to foster or claim a certain share of recycling aggregates in concretes. When this is achieved, even a higher substitution rate of primary raw materials by recycling aggregates as allowed by Austrian standards can be envisaged, as this is technically feasible and thus practiced in many other countries (Evangelista and de Brito, 2014; Silva et al., 2014). Thus, this measure does not necessarily require more research, but more political and entrepreneurial will. This finding is also relevant for many other cities that have a comparable large public sector like Vienna.

4.2.5. Recycling of waste debris to substitute raw-mix of cement raw materials in cement for concrete

Like with asphalt recycling, the substitution of the raw-mix for cement clinker is already practiced in Austria and very likely also in the cement plants that supply the major part of the cement demand of the city. However, considering that currently only about 10% of raw-mix for cement clinker production in Austria derives from mineral CDW, it is unlikely that the full potential of 84,000 t/yr based on a raw-mix substitution of 20% as determined in this scenario is recycled in that way. This increasing substitution would not only be beneficial to reach the sustainability targets of Vienna. It might also mean a reduction of the energy demand and greenhouse gas emissions in the cement industry, as the Al-Si in debris contains less water that has to be evaporated during preheating, and the Ca in debris is present also in forms not producing CO_2 during calcination, like CSH (Zeitlhofer et al., 2018). Whether these energy and greenhouse gas reductions overweigh the additional energy demand for milling the CDW debris in the raw mill, has to be further investigated in a full material, energy, and life-cycle assessment of integrated cement plants using primary clay or substantial amounts of CDW debris.

4.2.6. Unbound recycling gravel in road constructions

About 463,000 t/yr of recycling materials from mineral CDW can be recycled in unbound form. This recycling material would consist of mainly recycled gravel from ballast track and road excavations R_u (55% or 253,000 t/yr), recycling asphalt R_a (26% or 119,000 t/yr), concrete R_c (14% or 63,000 t/yr), and debris R_b (6% or 29,000 t/yr). With this average composition, also the criteria for most gravel applications should be met. As with recycling aggregates from CDW for concrete production, there is not much research demand for enabling this measure, as there is already a lot of literature available (e.g. da Conceição Leite et al., 2011; Guo et al., 2014; Huang et al., 2018; Rao et al., 2007). The question is more whether there is the political and entrepreneurial will to use more recycling materials from mineral CDW for this purpose.

4.2.7. Summary of scenario results

Table 4 summarizes the results of the scenarios for both, recycling of mineral CDW as well as the thereby reduced amounts of construction minerals consumed, and CDW to be landfilled and exported. These results are also displayed in detail in the supplementary materials table, sheet 4.2.7.

4.2.8. Further options for as sustainable management of construction minerals in Vienna

The circularity scenario considered selected measures to reduce CDW generation, as well as raw material consumption by recycling of CDW and avoided demolition of buildings. However, there are options not considered in the article to go even further, and two of these are described.

A further reduction of the raw material demand is possible, for instance by substituting parts of the concrete used for wall constructions by hollow bricks. The latter have a density of only 1 t/m^3 if compared to 2.4 t/m^3 for concrete. For this reason, a substantial reduction of the raw material demand can be expected, but has to be proofed by further research.

To reduce the export and landfilling of particularly CDW debris, more recycling options than the ones presented exist, including the use as sand for tennis courts, in landscape engineering, earth-based infrastructure, as addition to composts, and as light-weight aggregates in concrete in the city. The potential of these is not known and should thus be considered in future works based on the present study.

These future works, however, rely on the existence of reliable data for the status quo, and as this existence and reliability is not entirely present, it should be established. This will become even more important in the future, where it is projected that a growing population will also cause a higher material turnover in the construction sector, if not measures as presented in the article at hand and beyond are implemented (Lederer et al., 2020).

5. Conclusions

Like other cities, Vienna has set targets for the reduction of material consumption in the construction sector by substituting primary by secondary raw materials and thus making the city more independent from minerals raw material import, mineral CDW export and landfilling. The study at hand not only shows that Vienna is far away from meeting these targets, but also that are options to reach them, including re-use and recycling, but also waste reduction. Therefore, however, a number of technological, legal, and management measures are to be further elaborated in detail, not only in Vienna, but also in all cities with similar challenges and sustainability targets (Kalmykova et al., 2016; Prendeville et al., 2018). To which extent these will be implemented will decide on whether urban sustainable development targets may have a real impact on primary raw material consumption and waste disposal.

Credit author statement

Jakob Lederer developed the conceptualization and methodology, performed the formal analysis and investigation, collected the data, administered the project, acquired parts of the funding and wrote the article. Andreas Gassner provided data and calculations with respect to construction minerals demand and mineral CDW generation in the infrastructure sector, and he also reviewed the document. Fritz Kleemann carried out most of the groundwork underlying this article and validated the results. Johann Fellner reviewed and edited the document, co-developed the concept and methodology of the article, and acquired co-funding of the work.

Declaration of Competing Interest

We declare no conflict of interest

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2020.104942.

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