Urban Mining for Sustainable Cities: Environmental Assessment of Recycled Concrete

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Abstract. In the global economy, the efficient use of resources in the building sector has become a central issue for sustainable development. Urban mining is an increasingly important area in constructing and demolishing of buildings. This article applies urban mining as a key approach for circular economy. In terms of material efficiency, the highest potential is seen in the use of concrete manufactured from recycled aggregates. The town hall building of the city of Korbach (Germany) has been dismantled and will be rebuilt with use of recycled materials from the old building. A recycling concrete (RC-scenario) is assessed from end of life (EoL) to gate within the life cycle assessment (LCA) boundaries, in comparison with conventional concrete i.e. a business as usual (BAU) scenario. The environmental assessment is done based on the product material, energy and water as well as the climate footprint. The product material footprint is determined in terms of Raw Material Input (RMI) and Total Material Requirement (TMR) and the product energy footprint in terms of Cumulated Energy Demand (CED) for non-renewable resources. The product water footprint is assessed by the Available Water Remaining (AWARE) method and the product climate footprint by values from the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC). The footprints are calculated using the software openLCA with the LCA database GaBi construction materials. The RC-scenario shows no significant savings in terms of product energy, water and climate footprint, whereas advantages could be clearly seen in terms of the product material footprint. The method and selected footprints have proven to be suitable for the environmental assessment of urban mining as an approach for circular economy with regard to SDG11 and SDG12.

1. Introduction
The 2030 Agenda with its Sustainability Development Goals (SDGs) addresses the importance of the building and construction sector towards sustainable development [1].Concrete is one of the most widely used materials for infrastructure projects and buildings [2]. The construction industry is considered as a major cause of environmental impacts [3], in terms of primary raw material extraction [4], greenhouse gas (GHG) emissions [5], water and energy [6,7]. The aggregates for buildings accumulate in the built environment and significantly increase the construction material stock [8]. Different categories of material are generated in the end of life (EoL) phase of buildings, including materials that are worthy to be recycled and further used. While the use of recycled aggregates could provide a better environmental performance [9,10], recycling scenarios should be assessed regarding their overall resource and climate footprints to avoid problem shifting and trade-offs. A footprint analysis should be done according to the Life Cycle Assessment (LCA) method as defined in ISO 14040 and ISO 14044 [11,12]. Several LCA
studies, considering the production of recycled aggregates from concrete and their application in concrete production, have been reviewed. The studies cover the processing of concrete waste in different plants [9,10,13–21]. The use of both fine and coarse aggregates in shares from 20 to 100% were assessed. Some studies deal with differences in cement, water and admixture contents of concrete with recycled aggregates in comparison with concrete with primary aggregates [16,17] while others neglect possible differences [9,19]. As the results diverge depending on the case study assumptions like availability of natural resources as well as mix designs, the transferability of these studies to specific cases is limited [10]. Therefore, further research is required based on real data on specific and existing market products in order to supplement and validate existing data [20]. For the first time this study assesses a real urban mining project based on the product material, energy, water and as well as the climate footprint. In the future, the footprint analysis could become a key instrument for the sustainable management of construction projects with regard to SDG11 and SDG12, which are namely sustainable cities and communities and responsible consumption and production.

2. Methods and Data

2.1. Goal and scope of the footprint analysis

The town hall building in the city of Korbach (Germany) was selectively dismantled to promote environmental protection and circular economy. Following an urban mining approach, the new building will be rebuilt at the same place and is planned with maximum use of recycled materials from the old building. The new concrete structure will be built with recycled aggregates from the old building. A comparative footprint analysis, covering the product material, energy, water and the climate footprint, is done to compare the recycling of concrete in the urban mining approach (RC-scenario) with the conventional production of concrete (BAU-scenario). Main objectives of the research work are the development of an environmental assessment instrument within the LCA boundaries for urban mining in the building sector, the investigation of different scenarios to improve the environmental performance of recycled concrete and the collection of input data from the project in the city of Korbach (Germany) taking into account the transferability to other cases and locations.

2.2. Life cycle phases and functional unit

Figure 1 shows the considered life cycle phases including system boundaries for the footprint analysis according to the LCA methodology.

![Figure 1. Life cycle assessment boundaries of the footprint analysis](image)

Life cycle phases are defined according to EN 15804 [22] where C is the end of life (EoL) phase and A is the product phase (A1 raw material supply, A2 transport, A3 manufacturing). These phases are taken
as the basis for the Life Cycle Inventory (LCI) of the concrete produced with recycled aggregates (RC-scenario) in comparison with production of the conventional concrete in the BAU-scenario. Production of conventional concrete includes the cradle-to-gate processes (A) such as materials production of primary aggregates, cement, fly ash and cement (A1), transport of the materials to the concrete plant (A2) and the manufacturing process of concrete (A3). The RC-scenario includes the manufacturing of concrete with recycled aggregates (RC-concrete) which involves additionally the EoL phase: demolition of the old building and crushing concrete (C1), transport of the concrete rubbles to the recycling plant (C2) and the process of recycled aggregates production (C3). The RC-concrete implies 40 % of aggregates as recycled aggregates. According to the requirements in Germany, up to 45 % is allowable [23]. In ISO 14040 [11] the functional unit (FU) is defined as the quantification of the designated functions or quality characteristics of a product system. The purpose of the concrete considered for the comparative footprint analysis is defined by its possible applications and the strength class. Thus, 1 m³ of concrete (C25/30) is considered as FU.

2.3. Life cycle inventory
The LCI is done according to the life cycle phases as they are described in EN 16757 [24] and EN 15804 [22]. The main difference in the concrete production is the use of 40 % of recycled aggregates for the RC-concrete. The remaining 60 % are natural aggregates such as gravel, sand and crushed stones as used for the conventional concrete production. Therefore, RC- and BAU-scenarios share the cradle-to-gate LCI results of the remaining material constituents. The LCI for the EoL phase (C1-C3) is conducted using data collected from the demolishing site and recycling plant as well as data documented in the literature. Figure 2 shows the material and energy input and output flows of the processes in the recycling plant.

![Figure 2. Material and energy flows of the processes in the recycling plant](image_url)

The flows are calculated based on 625 kg of recycled aggregates required for production of 1 m³ of RC-concrete. Transport distance for the trucks from the construction site to recycling plant is 30 km. The transport performance is calculated with load factor of 50 % (100 % to the recycling plant and 0 % back to the demolishing site). C3 represents the manufacturing process of recycled aggregates in the recycling plant. The manufacturing process of recycled aggregates requires the input of electricity and diesel. Concrete rubbles are loaded into an impact crusher with an integrated over band magnet for iron removal (Figure 2). After the crushing and separation of steel scraps, the concrete rubbles are sieved into three different size fractions (0/8 mm, 8/22 mm and 22/70 mm). The recycled aggregates with sizes fraction 0/8 mm and 22/70 mm are used for backfilling purposes mainly in road construction (78 %). The recycled aggregates with size fraction 8/22 mm are further processed to be used for the RC-concrete production (22 %). A wind sifter is used to separate remaining wood and plastic waste from the recycled aggregates.
aggregates to meet the quality requirements for their use in concrete [26]. As the production process is a multi-output process the energy must be allocated to the recycled aggregates for backfilling and to the recycled aggregates for concrete production. Mass allocation is applied as the recycled aggregates have the same market value before further processing. The quantities of raw materials for production of conventional concrete are defined according to the relevant Environmental Product Declaration (EPD) with strength class of C25/30 [27]. The upstream processes to produce the constituents including the extraction of primary raw materials, transport and manufacturing are referring to the life cycle phase A1. Primary aggregates categories are gravel and crushed stone with size above 2 mm (coarse aggregates) in addition to sand with size below 2 mm (fine aggregates). Recycled aggregates are in size of 8/22 mm. 625 kg of recycled aggregates per m³ of concrete are used within the 40 % percent in the RC-scenario. Concrete mixtures are shown in Table 1 [43].

**Table 1.** Concrete mixture composition for business as usual (BAU) scenario and recycling (RC) scenario according to [27] and calculations based on [23].

| Scenario | Gravel (kg) | Crushed stone (kg) | Sand (kg) | Recycled aggregate (kg) | Cement CEM II (kg) | Fly ash (kg) | Additives | Total (kg) |
|----------|-------------|-------------------|-----------|-------------------------|-------------------|--------------|-----------|-----------|
| BAU      | 810         | 364               | 628       | 0                       | 290               | 60           | 1         | 2,153     |
| RC       | 371         | 84                | 628       | 625                     | 290               | 60           | 1         | 2,059     |

According to Mettke et al. [28] and Knappe et al. [29] there is no significant difference in the amount of cement used in the production of concrete in the BAU- and RC-scenario. The gross density of the primary aggregates is higher than that of the recycled aggregates [25]. An additional input of 176 kg water is considered. Life cycle phase A2 covers the transportation of concrete constituents from the place of production to the concrete plant. Transport distances from 106 to 180 km are specified for cement [27,30]. The transport distance for primary aggregates depends on the regional availability and varies between 30 and 60 km in Germany [27]. In the study, the concrete production takes place 50 km from the excavation of the primary aggregates [31]. The distance between the recycling plant and the concrete plant is 45 km. A summary of the transport distances is shown in Table 2.

**Table 2.** Transportation distance and share of the transport type for the supply of concrete constituents.

| Material           | Mean distance (km) | Share of transport type | Truck (%) | Train (%) | Ship (%) |
|--------------------|--------------------|-------------------------|-----------|-----------|----------|
| Natural aggregates | 50                 |                         | 88        | 2         | 10       |
| Recycled aggregates| 30                 |                         | 100       | 0         | 0        |
| Cement             | 140                |                         | 80        | 9         | 11       |
| Fly ash            | 100                |                         | 100       | 0         | 0        |

The proportions of the respective transport type (truck, train and ship) are based on information of LCA building material profiles by the German Association for Ready-mix Concrete [30]. A load factor of 50 % is considered for the transport due to 100 % in loading case and 0 % in the empty case. The production of the concrete (A3) requires an average of 4.43 kWh electricity, 0.26 l heating oil and 0.07 l diesel per m³ of concrete [32]. openLCA software [33] is used for the LCI modelling. The databases used in the model are the ‘GaBi Professional database’ and the ‘GaBi Extension database XIV: Construction materials’, released 2019 (service pack 38) [34,35], which are widely used for LCA of buildings [36].
2.3 Product footprints
The product material footprint is determined by two indicators: The Raw Material Input (RMI) and the Total Material Requirement (TMR) [37]. Both indicators are referring to the environmental impacts of material input within the LCA boundaries. The RMI measures the cumulative used raw material input for a specific product or service per FU i.e. the used extraction. The extraction process of primary raw materials is always associated with unused extraction. The unused extraction is the primary material which is moved and dumped for the extraction of the primary raw materials. Unused extraction is not further processed and has no economic value, e.g. the overburden of a mine. The TMR measures the total extraction of material from and within nature, as sum of used and unused extraction, per FU. The Product Energy Footprint is determined by the Cumulative Energy Demand (CED). The CED accounts for the life cycle wide direct and indirect energy consumption, including energy consumption for the extraction, production and disposal of raw materials [38]. The CED considers renewable and non-renewable energy resources. The principles for determining and reporting the water footprint are defined in ISO 14046 [39]. The working group "Water Use in Life Cycle Assessment" (WULCA) of the "UNEP-SETAC Life Cycle Initiative" has developed the method for calculating the water footprint [40]. Within the conventional life cycle assessment (LCIA) methods, there are several indicators with different calculation models, considering water consumption but not availability in the specific region. AWARE (Available Water Remaining) method can be used to determine the amount of water remaining in a catchment area or in a country less than the water requirements of humans, animals and plants. AWARE could address the potential vulnerability of a catchment area to water stress. For the calculation of the characterization factors, the variable AMD (availability minus demand) is used, which is made up of the water availability minus the human and environmental requirements in relation to the reference area. The product climate footprint is calculated based on the global warming impact (GWI) expressed in kg CO₂ equivalents per FU. The characterization model with a time horizon of 100 years is used [41], based on the GWP100 values of the International Panel of Climate Change (IPCC) [42].

3. Results
Figure 3 shows the results for the product material footprint measured in RMI per FU.

![Figure 3](image-url)

**Figure 3.** Product material footprint measured in raw material input (RMI) per 1 m³ of concrete (C25/30) for the business as usual (BAU) and recycling (RC) scenario.
The RMI is decreased by 30 % in the RC-scenario compared to the BAU-scenario. The results are dominated in both scenarios by the production of concrete constituents (A1) (more than 99 %). Main primary materials are natural aggregate and calcium carbonate. As aggregates are dominating the mass of concrete constituents, the use of 40 % of recycled aggregates can significantly reduce the amount of primary material extraction. The product material footprint measured in terms of TMR shows no significant differences as the unused extraction of concrete constitutes is relatively low.

At the same time, it is important to assess additionally the use of water and energy for the manufacturing of the recycled aggregates and consequently for the produced RC-concrete to avoid trade-offs in resource consumption and environmental impacts. Figure 4 shows the results for the product energy footprint measured in CED per FU.

![Figure 4](image-url)  
**Figure 4.** Product energy footprint measured in cumulated energy demand (CED) from non-renewable energy resources per 1 m³ of concrete (C25/30) for the business as usual (BAU) and recycling (RC) scenario.

The CED from non-renewable resources is 9 % decreased in the RC-scenario compared to the BAU-scenario, as the energy savings in the production of concrete constituents (A1) are higher than additional energy demand for deconstruction (C1) and waste treatment (C3).

Figure 5 shows the results for the product water footprint measured in weighted m³ of water used per FU. The savings in the production of concrete constituents (A1) are higher than additional demand for deconstruction (C1) and waste treatment (C3). Therefore, the product water footprint is decreased by 8% in the RC-scenario compared to the BAU-scenario. Usually the waste processing requires additional water [43]. In the case study, the water consumption was reduced by the application of a dry process.
Figure 5. Product water footprint measured according to AWARE (Available Water Remaining) method in weighted m$^3$ of water used per 1 m$^3$ of concrete (C25/30) for the business as usual (BAU) and recycling (RC) scenario.

Figure 6 shows the results for the product climate footprint measured in GWI per FU. The product climate is just decreased by 4 % in the RC-scenario compared to the BAU-scenario. The production of concrete constituents, mainly cement, has the biggest contribution in both scenarios: about 94 % in the RC-scenario and about 96 % in the BAU-scenario.

Figure 6. Product climate footprint measured in Global Warming Impact (GWI) per 1 m$^3$ of concrete (C25/30) for the business as usual (BAU) and recycling (RC) scenario.
4. Conclusions
The results of the footprint analysis show that urban mining is a promising approach for promoting sustainable cities (SDG11) and sustainable production (SDG12) taking into account the specific conditions of the case study in the city of Korbach (Germany). The material efficiency of the concrete production can be increased 30% although only a share of 40% of recycled aggregates is used as concrete constituents. In the BAU-scenario the content of crushed stones in aggregates is relatively high. Although stone crushing is very energy intensive, their use became profitable in recent years in Germany due to an increased shortage of gravel. Since the recycled aggregates first replace crushed stones, the savings in non-renewable energy consumption and respectively in GHG emissions are not significant in the RC-scenario. The footprint analysis and selected footprint indicators have proven to be suitable for the environmental assessment of urban mining and circular economy in the building sector. Further research work will cover the assessment of the resource saving potentials by an increased share of recycled aggregate as concrete constituents, variation of the process technologies by sensitivity analysis and consideration of uncertainties mainly for transport processes.

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