PLEA 2017 EDINBURGH

Design to Thrive

From Sink to Stock: The Potential for Recycling Materials from the Existing Built Environment

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Abstract: The urban built environment maintains the alluring prospect of being a source for our future resource needs. This work imagines new local recycling paradigms for concrete and masonry waste within an existing urban environment. Using Lisbon, Portugal as a case study, we proposed three context-specific material recycling scenarios to make use of mineral construction waste generated as the city's aging residential building stock is replaced over the next 30 years. We compared four scenarios – three recycling proposals and standard landfill disposal – in terms of production potential, land use, greenhouse gas emissions, and cost. The results show that from both an environmental and economic standpoint, recycling is not always the optimal solution. The impacts depend not only on the recycling processes and end uses, but also the avoided and added burdens consequent to changes in the existing system. Through this analysis, we identified the limiting factors and potential opportunities for improvement in the current processes of construction material reuse and recycling, in Lisbon and beyond.

Keywords: construction materials, circular economy, recycling, construction and demolition waste (CDW)

Introduction

Construction of buildings and infrastructure in cities accounts for over 35% of total global raw material consumption (Krausmann *et al.*, 2009). The injection of construction materials happens primarily while a city is growing, as the built environment expands to serve the increasing population. In the 20^{th} century, post-World War II urbanization fuelled tremendous growth, resulting in the first wave of major worldwide construction material consumption. As new cities continue to grow over the next century, we will face a second upsurge of material consumption (United Nations Department of Economic and Social Affairs, 2014).

While new construction is projected to grow, the existing building stock is simultaneously aging. Buildings that were constructed during the urban boom of the last century are approaching the end of their useful lifespans. Arguably, these buildings are not old. However, many are not well maintained and this is accelerating their demise. Over two thirds of Europe's housing stock was built after WWII and much of it is in need of major repair and renovation.

When these buildings are ultimately demolished (as projected in the coming decades), most will be sent to landfill (Thomsen, Schultmann and Kohler, 2011). Currently in Europe, roughly 530 million tonnes per year or 2 tonnes per capita of construction and demolition waste (CDW) is generated annually. Individual CDW recycling rates vary from one EU country to another, depending on each country's own regulations. In Denmark, for example, the reported recycling rate is 94% while in Greece and Portugal, the recycling rates are less than

10%. Regardless of the current rate, it is assumed that the amount of construction waste generated will continue to increase, roughly at the same rate as each country's economy (Bio Intelligence Service, 2011).

Instead of seeing the material in existing buildings as waste, is there an opportunity to see it as a reservoir for imminent construction needs? Namely, through deconstruction and recycling. Deconstruction is the methodically planned and highly controlled processes of taking apart a building with the aim of separating components and materials "to avoid down cycling, energy transformation and deposit into landfill as much as possible" (Thomsen, Schultmann and Kohler, 2011). In this work, we imagine the potential for implementing a deconstruction and material recycling scheme in an existing urban context.

Methodology

We imagined three new local recycling schemes for concrete and ceramic waste within Lisbon's existing urban system. The work is organized in three parts: First, we estimated the current material stock and projected material output based on the future end-of-life of the buildings. Second, we envisioned the waste processing scenarios (both the existing disposal scheme and proposed recycling alternatives) for concrete and ceramic waste. Finally, for each of the scenarios we calculated the production potential, landfill requirements, global warming potential, and economic cost.

This work examines a set of existing buildings in Lisbon, Portugal. The area of study consists of seven mixed-use, but primarily residential, neighbourhoods. We considered 750 single-family and multi-family buildings within the site, all constructed between 1946 and 2011. Data pertaining to the buildings was collected as part of the larger MIT Portugal Program's SusCity Project (Sousa Monteiro, Pina and Ferrão, 2015).

Current and Future Material in the Building Stock

The urban building stock is a reservoir for future "extraction." To evaluate the feasibility of this idea, we estimated the material intensity and throughput -- the inputs, outputs, and storage – over the buildings' lifetimes. Then, we probabilistically estimate the end-of-life of the buildings to determine when the embedded materials will become available.

Figure 1: Building archetypes and their material profiles

To estimate the quantity of materials in the existing buildings, we utilized five building archetypes that represent the buildings' architectural qualities and material compositions. The archetypes were developed by Sousa Monteiro, Pina, and Ferrão (2015).

An aging building with little architectural heritage value is especially susceptible to removal, due to real estate and economic market factors (Thomsen, Schultmann and Kohler, 2011). Most of the sample buildings are of this condition, and thus susceptible to this demise. Assuming that the buildings will reach their end-of-life as projected in the coming years, we calculated the concrete and ceramic output every decade from 2020 to 2049. The decadal averages provide a sense of the lower and upper bounds of the potential material output of the site. To calculate the output we employed a Weibull time-to-failure function (Bekker, 1980), adopting the shape and scale parameters from a similar study of US residential building lifetimes (Aktas and Bilec, 2012).

CDW Disposal and Recycling Scenarios

Currently most of the concrete and ceramic waste generated during demolition in Portugal is sent to landfill (Martinho *et al.*, 2015). We assumed the existing condition to be the default waste removal scenario. We envisioned three localized recycling scenarios as alternatives to the default (see Figure 2), each designed to keep the material within the local region to establish a circular economy of construction materials. In each case, a particular end use was specified for the recycled material: road construction, concrete paver block production, and structural concrete in building construction.

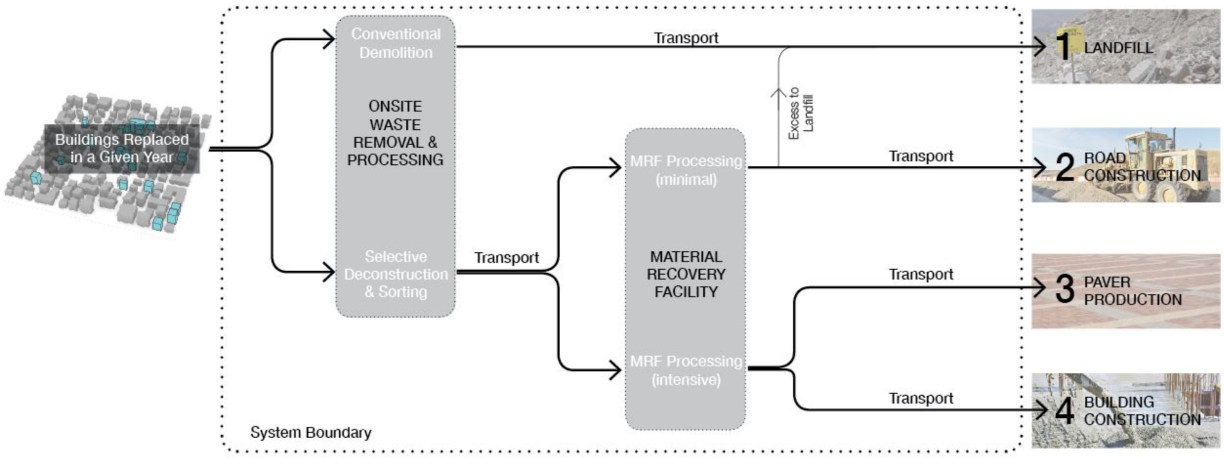

Figure 2: Concrete and ceramic waste processing and recycling scenarios.

The waste processing system includes the demolition or deconstruction of the buildings, the processing of waste into recycled aggregate and all transportation until permanent disposal or sale for use, as shown in Figure 2. The waste processing boundary does not include impacts on the end uses for the recycled aggregate or landfilling. These impacts, henceforth referred to as the *added and avoided impacts*, are considered separately. Transportation, particularly road transport via trucks, has a large impact on the environmental and cost impacts of CDW processing. To make any of the scenarios economically and environmentally viable, we limited the transport distances to reduce the impacts from trucking. Waste processing was limited to a distance of 25 km; landfill and end use drop-off was limited to 50 km; and raw material sourcing was limited to 100 km. The envisioned transportation pathways for each scenario are illustrated in Figure 3.

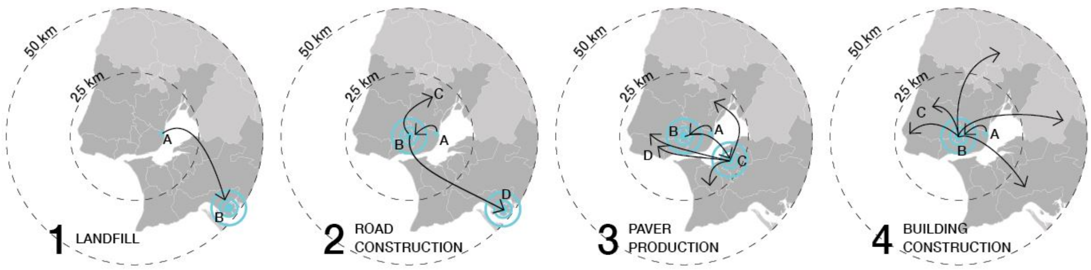

Figure 3: Proposed transportation pathways for the waste processing in the Lisbon metro area.

Calculating the Impact: Production Potential

Concrete and ceramic waste can be processed into recycled aggregate, which feeds a variety of secondary production processes. We considered three possible secondary end uses for the recycled material: *road construction*, *concrete paver block production* and *structural concrete*.

Recycled aggregate is often used as a sub-base layer in road construction. The 2-lane roadway considered in this scenario is based on an assembly proposed by Herrador et al. for an access road in Spain (2012). It consists of a 14cm pavement surface over a 30cm aggregate base layer, over is a second 50cm base of artificial aggregate. The recycled aggregate layer is composed of 75% concrete, 20% asphalt and 5% ceramic material, as per specifications provided by Herrador et al.

Concrete paving blocks used to create pedestrian walkways are a preferred application for recycled aggregate because, like in road construction, it allows for flexibility in quality and purity of the recycled material. The paver production considered in this scenario is based on a pre-cast concrete block proposed by Poon and Lam in their study of aggregate-to-cement ratios for this type of application (2008).

Using recycled aggregate for structural concrete in new buildings is the most appealing of the recycling proposals considered because it is the only truly closed loop system. The concrete mix considered consists of 50% recycled aggregate and 50% raw aggregate, based on Swiss data from Knoeri, Sanye-Mengual, and Althaus (2013). The use of recycled aggregate reduces the structural quality of the concrete, and necessitates a modified concrete mix in order to meet buildings regulations. Specifically, the mix requires an additional 10% cement, 10% fly ash, 50% water, and 30% superplasticizer. This modifications in the mix are considered in the secondary production calculations.

Calculating the Impact: Landfill Area Requirements

Landfill area is required for waste that is not processed and used as recycled aggregate. We assume that in the default demolition scenario, all the waste goes to landfill. In the recycling scenarios, some of the concrete and ceramic waste can go to landfill, as it may not satisfy the recycled aggregate quality required by the secondary uses. We size the landfill requirements based on numbers provided by Butera, Christensen and Astrup (2015): 1500 kg/m3 and 10m height.

Calculating the Impact: Global Warming Potential

Global warming potential (GWP) is a measure of the heat trapped by a greenhouse gas in the atmosphere. It is often measured, as it is in this analysis, over a 100-year period. For each scenario, we added the GWP of each process and activity to get a total GWP value. We employed lifecycle inventory data from the EcoInvent 3 database using SimaPro and the IMPACT 2002+ impact assessment method (PRe Sustainability, 2014; Wernet *et al.*, 2016).

Calculating the Impact: Costs

We estimated each scenario's overall cost based on recycling and waste processing industry data for Portugal (Coelho and de Brito, 2011; Coelho and De Brito, 2013). The cost includes all processes that are within the waste processing system boundary, from demolition to delivery of the recycled aggregate to the end use. For the three recycling scenarios, we also considered the potential earnings from selling the material. It is assumed that the concrete portion of recycled aggregate is sold at a rate of €2.76/tonne while the brick waste is given away at no cost (Coelho and de Brito, 2013).

Results

Production Potential

We assumed that 90% of the concrete and ceramic waste coming out of the sample buildings goes to the material recovery facility (MRF) for processing (and the remaining 10% is lost in onsite processing). This amounts to 19,910 tonnes per year recovered; of which, roughly 60% is concrete and 40% is ceramic. We assumed that, once in the MRF, 68% of the waste material is turned into recycled aggregate and 32% is lost as fines (Weil, Jeske and Schebek, 2006). Based on the material output from the MRF, we calculate the production potential of each recycling scheme:

In scenario 2, we estimated that annually 8,000 tonnes per of concrete aggregate and 5,500 tonnes of ceramic waste is available for use in the road. The production is limited by the amount of recycled concrete aggregate available, therefore only 500 tonnes of the ceramic waste is utilized. The remaining 5,000 tonnes of ceramic is assumed to go to landfill. Based on the amount of concrete recycled aggregate supply, approximately 1.5 to 2 km of new roadway can be constructed. Using the recycled aggregate results in 12,000 tonnes per year of avoided natural aggregate use.

In scenario 3, we assumed that 100% of concrete and ceramic recycled material, or 13,500 tonne per year, is used for paver production. The recycled material provides enough aggregate to produce 5.8 million paver blocks, enough to pave 35 to 40 km of 3m-wide pedestrian sidewalks. Using the recycled aggregate results in the avoided use of roughly 14,000 tonnes per year of raw aggregate.

In scenario 4, we assumed 100% of the concrete and ceramic recycled material is used as aggregate. This quantity can replace half of the natural aggregate required for the structural concrete, avoiding 23,700 tonnes of raw limestone sourcing per year. The mass of avoided raw material is greater than the mass of recycled aggregate used because of the difference in densities: 1890 kg/m3 for natural aggregate versus 1374 kg/m3 for recycled aggregate. The recycled aggregate coming from the buildings stock supplies enough material for roughly 19,700 m3 of structural concrete per year, enough to construct about 12 multi-family apartment buildings.

Landfill Area Requirements

In scenario 1, we assumed that all of the waste coming out of the buildings goes to landfill requiring a total area of 40,000 m^2 for waste over the 30-year period. In scenario 2, the road sub-base layer requires a mix of 75% concrete, 20% asphalt and 5% ceramic aggregate. Roughly 5,000 tonnes per year of ceramic aggregate is unused and assumed to be disposed in landfill, requiring a total area of 10,000 m^2 over the 30-year period. In both scenario 1 and 2, the landfill area was sized for the material output over the full 30-year study period (2020-

2049), as CDW landfills require long-term planning and land allocation. In scenarios 3 and 4, all of the concrete and ceramic-based recycled aggregate is used, thus there is no material sent to landfill. Material that is lost as fines during the recycled aggregate production process in MRF was excluded from the estimates in all cases.

Global Warming Potential

Global warming potential (GWP) results are presented first for the primary system (i.e direct impacts) and separately for the added and avoided impacts (Figure 4). For the primary system alone, scenario 1 resulted in the least amount of GWP. This is expected since the other scenarios have added activities and transportation associated with recycling. This is particularly true for scenarios 3 and 4, due to the added processing and transportation needed for a higher grade recycled aggregate. This result is in line with other similar studies of CDW recycling (Blengini, 2009).

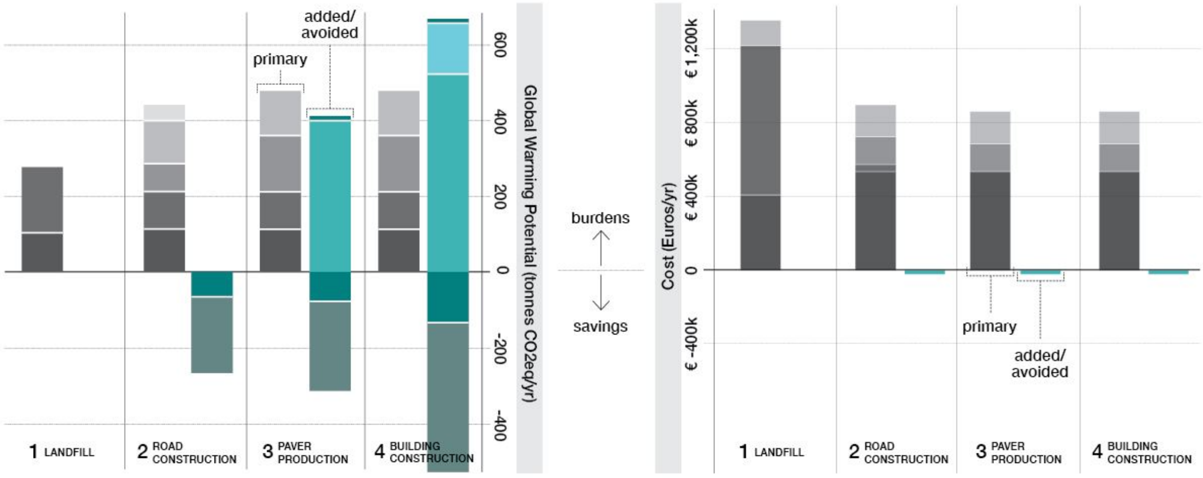

Figure 4: Global warming potential (tonnes CO2 eq per year) and costs (euros per year) for each process. The direct impacts in the system boundary are in grey; the added and avoided impacts of the associated end use processes are in color. Positive values are GWP/Euro burdens or "costs," negative values are savings.

The changes in the end uses resulting from the application of the recycled aggregate are significant and, if allocated to this system, can influence the GWP results greatly. In all recycling scenarios, there is a negative GWP for avoiding the use of natural aggregate. At the same time, in scenarios 3 and 4 there is an added impact for the increased use of cement and other materials to make up for the loss in strength of the concrete. Due to the high carbon intensity of cement production, the added GWP from the increased use of cement is about as much as the whole waste recovery and recycling process itself.

The added and avoided activities in the end uses could be alternatively allocated to the secondary processes. If this were the case, then these impacts would *not* be included in the analysis of these scenarios. Whether the impacts are included or not, it is useful to see the magnitude of environmental consequences resulting from the changes required in the end use processes relative to the waste recycling processes.

Costs

The costs include all processes within the waste processing system boundary, from demolition to delivery of the recycled aggregate to the secondary end use. For the three recycling scenarios, the potential earnings from selling the material were also considered. All three recycling scenarios have lower net cost than the disposal case primarily due to the high landfill tipping fees (Figure 4). The tipping fee is assumed to be €41/tonne for mixed CDW as per Portuguese industry data (Coelho and de Brito, 2011). The results show that while the recycling schemes have added processing and transport activities, the high fee for disposing the material in landfill results in roughly 50% increase in cost over any of the recycling scenarios. It should be noted that the cost analysis does not consider changes in the cost of the secondary end use production.

Results Summary and Analysis

	1 LANDFILL	2 ROAD CONSTRUCTION	3 PAVER PRODUCTION	4 BUILDING CONSTRUCTION
Production Potential (variable)	-	✓ 2 km new roads per year	✓ 35 km new sidewalks per year	✓ 12 new apartment buildings per year
Landfill Area (m2)	✗ 40,000 m2 for 30 year period	10,000 m2 for 30 year period	✓ -	✓ -
Global Warming Potential (tonnes CO2eq/yr)	274 (+/- 84)	✓ 174 (+/- 230)	✗ 572 (+/- 221)	✗ 616 (+/- 302)
Cost (euros/yr)	✗ € 1,358,000 (+/-67,000)	€ 885,000 (+/-88,000)	✓ € 845,000 (+/-88,000)	✓ € 845,000 (+/-88,000)

Figure 5: Summary of results for the four scenarios.

There is no scenario that is advantageous across all categories, as illustrated in Figure 5. In the three recycling scenarios, waste has a production value and contributes to the creation of something new (either roads, pedestrian pathways or buildings). The societal value of each end use depends largely on the local demand for the product in question. The environmental impacts – measured in terms of GWP (a global impact) and land use for landfill (a local impact) – have an inverse correlation. Namely, the recycling scenarios require additional processing and transportation, increasing the overall GWP; at the same time, using the material means that less waste is sent to landfill. Lastly, the landfill disposal scenario costs over 50% more than all of the recycling scenarios. This is due to the high landfill tipping fees. There is a minor cost distinction between the recycling proposals themselves, as the waste processing to create the aggregate is similar in each case. However, this cost analysis does not consider additional or avoided expenses in the secondary production processes. In summary, based on the four impacts considered, there is no clear winning scenario. The preferred option is in large part dependent on the local needs, economic conditions and environmental priorities.

Conclusion

Can we utilize the materials embedded in our existing buildings as a resource to feed the next generation of cities? In this work, we examined this question by analysing three site-specific schemes to locally recycle concrete and ceramic waste. We considered the impacts of each scheme in terms of production potential, land use, global warming potential, and cost. The results show that, from both an environmental and cost standpoint, the circular material paradigm is not always the optimal solution. The impacts depend not only on the recycling processes and end uses, but also the avoided and added burdens consequent to changes in the existing system. The results highlight the need for a nuanced approach to the topic of waste management and resource recovery. It is often the case that recycling is an environmentally preferable alternative to landfilling. However, as shown in the results of this analysis, there are exceptions. Ultimately, we must develop more thoughtful, efficient, and long-term holistic solutions for material use and reuse in construction.

Acknowledgements

Generous support for this work was provided by the MIT Portugal Program. Thank you to Jonathan Krones for his assistance and guidance.

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