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Transportation matters – Does it? GIS-based comparative environmental assessment of concrete mixes with cement, fly ash, natural and recycled aggregates

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ABSTRACT

The urban world is expanding and densifying fast. This requires and produces huge amounts of new construction materials and construction and demolition waste (CDW) every year. Concrete is not only the most important construction material in terms of sheer amount but also regarding embodied greenhouse gas emissions. Alternative concrete mixes have been developed by introducing supplementary cementitious materials (e.g. fly ash (FA)) and CDW (e.g. recycled aggregates (RA)). So far, environmental assessments focus mostly on the production of concrete mixes without considering the transportation-related impacts. This paper appraises the importance of transportation-related impacts of raw materials for concrete production and proposes a new method combining Life Cycle Assessment and geospatial analysis of road transportation of materials. Environmental impacts (EI) of different mixes are assessed for the specific locations of concrete plants. Traditional and alternative concrete mixes are compared to choose site-specifically the mix with lower impacts. For that purpose, two Portuguese cities were considered as case studies. The new method uncovers if and how location of supply and demand for concrete production is important. The results show that for traditional concrete and for mixes incorporating low FA ratio and/or RA, transportation does not matter. However, it matters when choosing between already drastically improved mixes: then, distances from raw materials suppliers to concrete plants can tip the scales of total EI. In fact, the distances to FA and recycling plants influence the selection of the most environmental friendly concrete mix. The method can be applied to other case studies and materials.

1. Introduction

1.1. Material requirements for growing cities

The world's urban population has exceeded the rural population in the first decade of the 21st century (UN, 2014). Cities are a constantly changing environment and are subject to expansion and densification that require huge amounts of resources. In fact, construction materials are already the world's single largest material stock and flow (Schandl and West, 2010). Concrete, commonly made with cement, aggregates and water, is the most used man-made material in the world nowadays (de Brito and Saikia, 2013). It is used for all types of infrastructure, structural and non-structural purposes. In the European Union (EU) alone, 215 million m^3 of ready-mixed concrete were produced in 2015 (ERMCO, 2016). Besides this immense demand of raw materials, the construction sector is also one of the biggest industries in Europe regarding its production of waste, yearly about 100 million tons of construction and demolition waste (CDW), which also causes significant environmental impacts (EI) (Marzouk and Azab, 2014).

Data on the annual growth rates for buildings reveals that the European crisis in the building sector, which had its peak between 2008 and early 2013 and led to a decline in the total construction all over Europe, is slowly recovering. In fact, the construction sector is growing again in Europe (Eurostat, 2017), especially for new residential dwellings and retrofitting activities. This growth is already verified in Portugal, including demolition works (INE, 2016). An increased amount of

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construction materials is needed and there is the challenge on how to handle resulting demolition waste in an efficient and sustainable way.

1.2. Scarcity of resources

The increasing amount of required construction materials is closely linked to the challenge of resource scarcity of basic raw materials to produce concrete. This is due to the sheer amount of needed material and to the difficulty to open new quarries in densely populated areas. The result is often the use of quarries that are distant from the place where the material is actually needed. It therefore increases transportation costs and impacts. Even though natural aggregates (NA), which are used to produce concrete, are commonly considered an unlimited global resource (Habert et al., 2010), they can actually be critical at the local level, as shown by Ioannidou et al. (2017). These authors studied the Swiss case and focused on the supply risk. Their suggestion is that in some cases within Europe it might be more economically viable to transport aggregates from neighboring countries than from national sources.

The increased activity of the construction sector and resulting CDW, also presents the problem of how to handle the waste. Many countries do not have specific regulations allowing precise quantifying and sorting CDW, even though in terms of quantity it is a greater problem than municipal solid waste (Coelho and de Brito, 2011). Different EU countries are trying to enforce CDW to previous sorting to increase the amount of recycled materials. In Portugal, for example, a decree-law aims to reduce the amount of CDW that goes to landfill (Freire et al., 2016). That much of the CDW goes directly to landfill is a loss of (secondary) resources, especially considering the mentioned criticality of aggregates for concrete production, and imposes an additional environmental burden because of the transportation to the landfill site. Therefore, it is important to study environmental advantages of recycling CDW.

Concrete is one of the biggest contributors to greenhouse gas emissions (GHG) but offers multiple opportunities to improve its environmental performance. For example by reducing the amount of virgin NA using recycled aggregates (RA) in the concrete mix. Recycled materials can be sourced from CDW and can be crushed concrete, bricks or tiles (Kleijer et al., 2017).

1.3. Advantages and disadvantages of RA concrete

Some studies have revealed that there is actually no clear advantage regarding impacts when using RA compared to NA without considering transportation (Kleijer et al., 2017). Also, there are concerns on the reduced compressive strength of RA concrete, which is usually counteracted with more cement, the most GHG intense material in a concrete mix (Li, 2008). The resulting higher water-cement ratio then asks for superplasticizer (SP) to maintain the workability of the concrete mix (Bravo et al., 2017), that together with cement cause higher EI.

RA only shows clear benefits for land use and respiratory inorganics (Estanqueiro et al., 2016). A significant advantage only arises when concrete mix incorporates fine RA in the production, instead of disposing of RA in landfill. This reduces the overall EI of RA concrete. Braunschweig et al. (2011) concluded in their study of Zurich that RA shows benefits for the production of low strength concrete, while the impacts of RA and NA production for high quality structural concrete are similar. Apparently, the main advantage when analyzing the environmental performance of RA concrete arises from avoiding landfill (Knoeri et al., 2013). Yazdanbakhsh et al. (2017) did an urban scale study, looking at the feasibility to use RA for all types of construction projects in the New York City area, and suggested that no significant reduction of impacts can be achieved, but the location of recycling and raw material production plants can influence impacts. The closer to the concrete plant, the smaller the transportation impact and the better the overall performance will be.

1.4. Importance of considering transportation in life cycle assessment (LCA) studies

Most often, plants that recycle CDW are close to densely populated areas, for simple economic reasons (De Melo et al., 2011). This makes sense when considering the correlation between higher population density and increased CDW generation, as well as for higher building density and increased CDW generation (Bernardo et al., 2016). However, other scholars found that CDW generated in peri-urban and rural areas is not negligible, often coinciding with hot spots for new residential construction (Mihai and Grozavu, 2017). Overall, recycling facilities close to cities seem reasonable (Yazdanbakhsh et al., 2017). Nevertheless, especially for areas that are further away from recycling plants, a detailed assessment of transportation distances and corresponding impacts, from and to site, is required to decide whether it is environmentally viable to use RA. Several authors already raised this specific question, but there is no method yet that can provide reliable results. Ding et al. (2016) measured EI related to the production of concrete with NA versus RA in China. They found that the small benefit of RA concrete is due to shorter transportation distances. Furthermore, transportation distance, besides cement content, is the main contributor to GHG emissions and energy consumption in concrete. Marinković et al. (2010) conducted a Life Cycle Assessment (LCA) for NA and RA concrete for structural purposes using experimental evidence. They also found that transportation distance and mode for NA and RA are critical for the magnitude of total EI.

1.5. The spatial aspect when choosing raw and construction materials

Aggregates are a high-bulk commodity with a low monetary value per mass unit. Compared to production of aggregates, their transportation shows a significant economic and environmental impact (Langer et al., 2004). As mentioned, differences for NA and RA concrete in comparable LCA studies are very small and usually do not allow precise identification of the best alternative. Therefore, uncertainties in such studies become crucial. Kleijer et al. (2017) claimed that transportation of ready-mix concretes has a high impact while underlying high uncertainties. During the last years, regionalized (or geography-specific) assessments, or scenario-based sensitivity analyses (Estanqueiro et al., 2016), are becoming more important. They consider site-specific production conditions and transportation characteristics and increase accuracy.

Geographical information systems (GIS) are computational resources that are widely applied to assess dynamics in time and space. The regionalization of LCA is known to improve its accuracy, and can be achieved by GIS (Yang, 2016). For example, Mastrucci et al. (2016) made use of a geospatial characterization of the building materials stocks for different end-of-life scenarios in a small Luxemburgish city. They showed the benefits of characterizing building materials in space to develop recycling strategies. In another example, data from a LCA study on cocoa farming in Peru was used to identify spatial and temporal trends in GHG emissions, by implementing the LCA results into GIS (Raschio et al., 2017). The geographic location is important to assess the quantity and place of occurrence of environmental emissions and their effects (Yang, 2016; Faleet, 2016).

However, acquiring the necessary spatial data for regional assessments is challenging. While producing factories often know their direct suppliers, they are usually not informed about the entire supply chain and consumer phase (Hellweg and Canals, 2014). This is the reason why averages and generic data are frequently used to model transportation in LCA studies of RA concrete. In a compared LCA of NA and coarse RA (Estanqueiro et al., 2016) averages were used for distances between quarry, concrete plant, construction site; demolition site and fixed or mobile recycling plant. Braga et al. (2017) used data from Ecoinvent to consider transportation of raw materials to concrete plant. Exceptions to the use of average data that could be found in the