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Integrating life cycle assessment and multi-objective optimization for economical and environmentally sustainable supply of aggregate

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ABSTRACT

Aggregate is one of the most widely used construction materials in the world. Due to its global extensive use, extracting and transporting the huge amounts of aggregate result in significant environmental impacts and economic burdens. Therefore, selecting aggregate supply sources with low environmental impacts and material cost has become important, particularly for the regions with limited local resources. This study presents an integrated model based on life cycle assessment and multi-objective optimization to plan the optimal aggregate supplies from different sources. The results can help stakeholders formulate sustainable material supply strategies that minimize the associated environmental impacts and material cost while meeting the demand and emission targets. As over 70% of the aggregates used in Hong Kong are imported across the border, the aggregate industry of Hong Kong is used to elaborate the model development and optimization in this paper. The results show that the use of locally-recycled aggregate should be encouraged as it is beneficial from both environmental and economic perspectives. However, due to the lacks of public perception and engineering experience, the annual supply and consumption of recycled aggregate are still very low (i.e., 0.3% market share). The local industry should overcome the application barriers and increase the supply capacity of recycled aggregate in order to maximize the environmental and economic benefits. Furthermore, use of locally-quarried aggregates can help achieve emission reduction targets, but at the expense of increased material cost. The acceptable emission targets in Hong Kong can be achieved under current aggregate production capacities, but medium and ambitious emission caps are too stringent and require substantial improvements in local aggregate supplies. It is suggested that material availability from various sources should be considered when formulating the reduction targets.

1. Introduction

According to Mehta (2002), around 9 billion tonnes of aggregate are extracted and used every year. Mining, processing and transporting the huge amounts of aggregate require considerable quantities of energy, produce large amounts of carbon emissions, and adversely influence the ecology of the earth (Abbas et al., 2006). The large consumption of aggregate has negative effects on the environment and arises large economic burdens for the construction industry. Hence, identifying economical and environmentally sustainable aggregate supply sources becomes important for industrial decision makers.

The environmental impacts of aggregate are more severe in regions that have limited local supply, such as Hong Kong, due to the heavy weight of aggregate. As shown in Fig. 1, the annual aggregate demand in Hong Kong is around 14.66 million tonnes, with 75% imported from China and 25% provided locally either from quarries or waste recycling facilities. A fundamental difficulty in selecting the supply sources is the need to simultaneously consider multiple competing objectives, which are aggregate availability, environmental concerns, and material cost. Importing aggregate from China to Hong Kong can ensure the supply reliability. However, transportation of the heavy and bulky aggregate over long distances (around 120 km) significantly increase fuel consumption and air pollutant emissions during the product life cycle (Calkins, 2008). With emission reduction targets being proposed for next few decades (Environment Bureau, 2013; EPD, 2010), the industry prefer more sustainable sources for the aggregate supply. Obtaining aggregate from local suppliers can reduce the transportation

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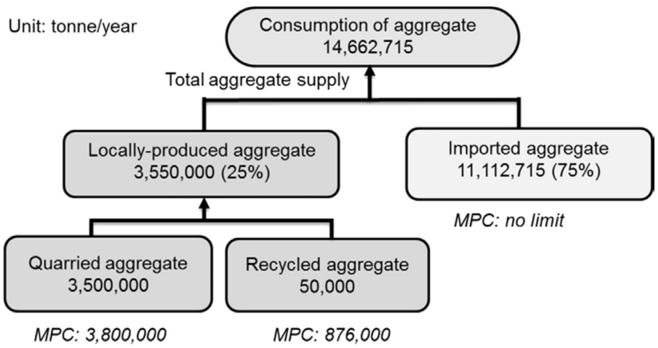

Fig. 1. Supply and maximum production capacity of each aggregate source in Hong Kong.

distance and air emissions, but Hong Kong has a few indigenous mineral resources and the local suppliers have limited production capacity to deal with the aggregate demand. Recycled aggregate incurs relatively low environmental impacts due to the prevention of raw materials and energy sources (Calkins, 2008). In Hong Kong, recycled aggregate is free to users (Hong Kong Housing Authority, 2011) but its annual production is only 0.3% of the market share with a low supply level to the local industry. The situation in Hong Kong is similar to many cities in China or other regions, some of which are closing their local quarries due to urbanization and increasingly depend on imported aggregate. Every type of aggregate source has its advantages and shortcomings in terms of supply reliability, environmental impacts, and material cost. The sources should not be chosen for satisfying one objective while sacrificing the others, because all objectives are important for stakeholders. In order to achieve multiple competing objectives, the decision makers should embrace a sustainable material supply strategy that can simultaneously reduce the environmental impacts and material cost while meeting the demand and emission target setting by the industry.

Multi-objective optimization (MOO) has been considered an effective approach to analyze problems with more than one competing objective (Coello Coello, 2006; Deb, 2005). The MOO technique has been applied in supply chain management, green building design, waste management and energy efficiency improvement (Diakaki et al., 2008; Marler and Arora, 2004; Ren et al., 2010). For example, Wang et al. (2005) formulated the objective functions of life cycle cost and exergy consumption for buildings by defining the orientations, window, and door types as design variables. Minimizations of cost and exergy consumption were executed simultaneously and the results were optimal design solutions to the analyzed objectives. For another example, Wang et al. (2011) proposed a MOO model to design a green supply chain which includes minimizing the total investment cost and carbon emission. However, the application of MOO for the sustainable sourcing of construction materials is relatively lacking. Several issues should be addressed prior to the optimization. First, the environmental impacts of aggregate production should be evaluated for providing the modeling data in optimization. Second, the objective functions formulated in the earlier studies can consider only one environmental impact category. Since this study considers different emissions from aggregate production, there is a need to combine various impact categories into one objective function.

Life cycle assessment (LCA) can evaluate the potential environmental impacts during a product's life cycle (ISO 14040, 2006; ISO 14044, 2006). LCA also provides systematic approaches to characterize the environmental influences and unify different impact categories using normalization coefficients. The integration of LCA with MOO optimization can potentially address the issues of environmental modeling data and impact category combination. There have been some studies evaluated the environmental profile of aggregate production (EcoInvent, 2013; Sichuan University & IKE Co., 2008). It is noted that much of the studies have been focused on process efficiency and production technology to reduce the environmental impacts (Jullien et al., 2012; Lowndes and Jeffrey, 2007). In addition, the previous studies were often carried out over a "Cradle-to-Gate" life cycle, with particular emphasis on the manufacturing processes and exclusion of product transportation. However, transportation of the bulky aggregate consumes large amounts of energy and contributes high proportions of atmospheric emissions (Calkins, 2008; Fry and Wayman, 2007), and therefore product transportation should also be included in LCA of aggregate.

The ultimate objective of this study was to develop an optimization model for planning the aggregate supplies from different sources in order to minimize the environmental impacts and material cost, taking into account the supply capacities, demands, and emission reduction targets. The results can provide a decision support base for more environmentally-sustainable and economically-efficient supply of aggregate. As the problem is more challenging in the regions that have limited local resource supply (such as Hong Kong where over 70% of the aggregate is imported), the aggregate industry of Hong Kong is used to elaborate the model development in this paper. To achieve the objective, LCA and MOO were integrated, in which LCA evaluated the environmental impact categories and provided normalization coefficients to convert different impact categories into one objective function. The task of MOO was to optimize the objective functions of environmental damage and material cost by searching for the optimal aggregate supplies. Considering the importance of product transportation, a "Cradle-to-Site" system boundary was defined which covers the emissions from aggregate transport.

2. Material and methods

2.1. LCA method used in analysis

2.1.1. Goal and scope definition

This study considers three aggregate sources: locally-quarried, locally-recycled, and imported aggregate. Fig. 2 outlines the manufacturing process for each source including the system boundary in this study. The first step of manufacturing quarried aggregate is blasting and drilling operations. The loosened hard rocks are transferred by heavy goods vehicles to processing facilities for crushing, scalping and screening. Finally, the aggregate is handled by stockpiles and transported to users. Recycled aggregate is derived from construction and demolition (C&D) wastes. The recycled aggregate suitable for construction works is extracted from the broken rock and demolished concrete rubble (Hong Kong Housing Authority, 2011). The waste materials are delivered to treatment plant for sorting, crushing, magnetic and manual separation to remove impurities, before they are transported to users. Imported aggregate is dredged primarily from rivers or mined from open pits in source locations of China and then transported by inland vessels to the wharfs in Hong Kong. As shown in Fig. 2, the "Cradle-to-Site" system boundary comprises processes from raw material acquisition, through manufacturing to product transportation. It is noted that recycling C&D wastes is the end-of-life stage of previous material life cycle and should be excluded from the system boundary of recycled aggregate production. This study uses the functional unit of 1 kg atmospheric emissions per 1 kg for