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Quantifying potential anthropogenic resources of buildings through hot spot analysis

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ABSTRACT

This study estimates the amount of urban ores in Taipei City between 1965 and 2014 by analyzing data of the buildings through statistics and geographical information systems (GIS). Hot spot analysis (HSA) is introduced to assess the location of resources. Our results show that up to the year 2014, 186 Mton of construction materials were accumulated in Taipei, and the per capita total building material stock was 68 ton. In the short term, the hot spots with development potential are Da'an (Zone I) and Zhongshan (Zone II) Districts in Taipei City. Zone I (0.1 km^2) stored 180 kton of materials; while Zone II (0.6 km^2) stored 119 kton of materials. This study provides quantitative data on urban ores with high spatial and temporal resolution for enhancing material recycling planning and management. Material stocks could then combine with the material flow to build a dynamic material flow model for assessing the quantity of extractable urban ores, and the feasibility of exploitation in the future.

1. Introduction

Urban mining is one of many practical strategies for transforming a society into a circular economy (CE) (Brunner, 2007; Cossu, 2013; Cossu and Williams, 2015; Pauliuk et al., 2012; Simoni et al., 2015; Schiller et al., 2017). As natural resources are depleting, the traditional linear economy (take-make-dispose) is no longer practical. Converting to a CE would be a solution towards sustainable development (Frosch and Gallopoulos, 1989). CE is based on the concept of "cradle to cradle," meaning that no waste is generated in the whole system and that all outputs are the inputs of the next process (Korhonen et al., 2018; McDonough and Braungart, 2010). This idea aligns with industrial ecology (IE), which aims to build a closed-loop system to minimize the production of undesirable by-products (Graedel et al., 1995).

Over the past two centuries, driven by industrialization and urbanization, enormous amounts of raw material have been extracted from nature to become a part of the anthroposphere and aggregated into urban ores. These ores are regarded as material stocks (MS) in socio-economic metabolism (SEM), and exploiting these MS through various technologies is called urban mining (Cossu and Williams, 2015; Graedel, 2011; Halada et al., 2009; Jacobs, 1961; Johansson et al., 2013; Kennedy et al., 2007; Lederer et al., 2016). Similar to traditional mining, urban mining involves stages of prospection, exploration, development, and exploitation (Hartman and Mutmansky, 2002). Prospection is done through desk research to find areas with urban mines; exploration is then carried out by quantifying, locating, and pricing the mines; and finally, the feasibility of exploitation is assessed. In this sense, urban mining provides a way to fully utilize anthropogenic resources and to recycle the materials in SEM, supplanting raw materials extraction from nature. Cities with a rich MS storage are expected to have higher potential to transform into a CE through urban mining.

Numerous SEM studies have investigated material flows at the macro level, but there are few studies that focus on material stocks at the micro scale (Fishman et al., 2014; Lederer et al., 2014; Tanikawa et al., 2015). Since this MS is of great potential to be developed into useful resources, they have to be accurately quantified and carefully managed. As a prime example, buildings are one of the most abundant resources in a city that contains various construction materials such as concrete, bricks, steel, glass, wood, and aluminum. (Hashimoto et al., 2009, 2007; Huang et al., 2013; Kleemann et al., 2017; Tanikawa et al., 2015; Tanikawa and Hashimoto, 2009; Wang et al., 2016). Buildings are constructed for the use of satisfying human demand for accommodation, which are the living spaces of the urban citizens; they also

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functionally indicate a city's standard of living (Pauliuk and Müller, 2014; Tanikawa et al., 2015).

Resources are consumed, and pollutants are generated during the construction, operation, and disposal of these buildings (Kennedy et al., 2007). During the construction stage, massive construction materials are needed, often consisting of a huge amount of minerals such as gravel, limestone, clay, iron ore, coal, silica ore, and bauxite. This leads to the depletion of natural resources, which causes severe environmental problems. For instance, cement and gravel are used to produce concrete. In cement production, a large amount of energy is needed, and considerable quantities of CO_2, NO_X, SO_2, and dust are generated. Gravel extraction particularly causes topographical changes and irreversible environmental damage (Heeren, 2017; Khasreen et al., 2009; Wang et al., 2016; Zabalza Bribián et al., 2011). After construction, resources exist in the city as in-use stock (Kapur and Graedel, 2006; Pauliuk and Müller, 2014; van Beers and Graedel, 2007). Fewer resources are consumed during the operation stage, mainly water, electricity, and natural gas from human activities (Heeren, 2017; Ibn-Mohammed et al., 2013; Zabalza Bribián et al., 2011). When buildings come to the end of their life, or a disastrous event occurs, the MS will become waste and a burden to the city (García-Torres et al., 2017; Jin et al., 2017; Miatto et al., 2017a; Tanikawa et al., 2014). Thus buildings can potentially influence natural resources storage and environmental quality, which both may benefit from a systematic analysis of the quantity of urban construction material reserves to encourage material recycling, minimize waste generation, and reduce resource consumption.

Basic information about urban ores includes quantity, composition, spatial attribute, and age (Brunner, 2011; Graedel, 2011; Tanikawa et al., 2015; Tanikawa and Hashimoto, 2009). Most of the previous MS studies have usually conducted top-down material flow analysis (MFA) on a macro scale. This research has received criticism for its failure to provide more than basic urban ore information, and for treating the economy as a black box, only considering a net addition to stocks (NAS) as a balancing factor for inflows and outflows (Augiseau and Barles, 2017; Ciacci et al., 2017; Tanikawa et al., 2015).

Though bottom-up MFA could obtain information on a smaller scale, it only evaluates the NAS without knowing the quantity of the accumulated stocks in a particular area, and the time and labor costs involved in performing MFA are high (Ciacci et al., 2017; Kral et al., 2014; Wang et al., 2016). It thus is usually only used to evaluate a single material in a specific year (Kleemann et al., 2017). Tanikawa and Hashimoto (2009) suggest a bottom-up material stock analysis (MSA) using four-dimensional Geographical Information Systems (4D-GIS) to analyze the spatial and temporal distribution of urban ores in Salford Quays and Wakayama City center. Bottom-up MSA can provide MS information at a higher spatial resolution relative to MFA with multi-material. Some recent studies on building and network infrastructure construction such as pipelines and underground railways have also been conducted with spatial MSA (García-Torres et al., 2017; Huang et al., 2017; Kleemann et al., 2017; Lederer et al., 2016; Marcellus-Zamora et al., 2016; Mastrucci et al., 2017; Oezdemir et al., 2017; Ortlepp et al., 2016; Stephan and Athanassiadis, 2017; Tanikawa et al., 2015; Tanikawa and Hashimoto, 2009; Wallsten et al., 2013).

Using bottom-up MSA, the quantity of urban ores in a district can be calculated by the object total multiplied by material intensity (Hashimoto et al., 2009; Kapur and Graedel, 2006; Wallsten et al., 2013; Tanikawa et al., 2015; Kalcher et al., 2017; Kleemann et al., 2017; Maung et al., 2017; Marcellus-Zamora et al., 2016; Miatto et al., 2017b; Parajuly et al., 2017). The object refers to the product that stores the urban ores, such as buildings, vehicles, and electronic devices; while object total means the total amount of objects within the district, which can be expressed in total weight, total volume, and total gross floor area (TGFA), etc. Material intensity represents the material content of the object.

While traditional MFA has its drawbacks, one of the major criticisms of bottom-up MSA is the difficulty in procuring accurate parameters, resulting in an uncertainty (Parajuly et al., 2017; Stephan and Athanassiadis, 2017; Tanikawa et al., 2015). Object total is often estimated by floor area mutiplied by building height or total number of floors (Kleemann et al., 2017; Mastrucci et al., 2017; Tanikawa et al., 2015; Tanikawa and Hashimoto, 2009), and information on material intensity, building structure, and the construction completion time is usually difficult to obtain (Kleemann et al., 2017; Marcellus-Zamora et al., 2016; Miatto et al., 2017a; Stephan and Athanassiadis, 2017; Tanikawa et al., 2015; Tanikawa and Hashimoto, 2009). If the building structure is unknown, it will be difficult to obtain the accurate corresponding material intensity; and if the construction completion time is unknown, the building age cannot be estimated, so the time to reclaim building MS cannot be calculated.

This study aims to accurately capture urban ore's basic information and assess potential locations for extraction. Detailed building statistical data includes the date of construction, building structure, use of buildings, TGFA, number of floors, building address, etc. GIS data were acquired from the Taipei government to analyze the potential construction material stocks in Taipei for the past 50 years. Correlation analysis of the building structure, total floor numbers, and building age is also conducted. Locations with a cluster of old buildings have a higher exploitation potential, as urban ores can only be extracted at the end of a building's lifespan (Brunner, 2011; Lederer et al., 2016), and extraction efficiency is higher with denser urban ores. To evaluate the existence of old building clusters, the Getis-Ord's $Gi^*(d)$ statistic of hot spot analysis (HSA) is conducted. HSA is a spatial autocorrelation analysis that aims to understand if an event would create spatial clusters, and if that clustering would affect the surrounding areas (Odland, 1988); while Getis-Ord's $Gi^*(d)$ can not only indicate the presence of local clustering, but also the clustering of locations and intensity as well. This method is often used in social science research such as criminology and epidemiology. Crimes are not geographically random distributed, but with high tendency of clustering, which called the crime hotspots. Methods for testing spatial clustering like Getis-Ord's $Gi^*(d)$ are commonly used to detect whether criminal behaviors clustered in the district and to spot the location, so the resources of the police force can be allocated properly (Eck et al., 2005). Besides, epidemic and emergency medical incidents also show a clustering nature. Using Getis-Ord's $Gi^*(d)$ to pinpoint the hotspot enables the government to concentrate on anti-epidemic work and to efficiently allocate medical resources (Ahmad et al., 2015; Kao et al., 2017). It is believed that the development of building constructions also possesses this clustering tendency, thus, this study used Getis-Ord's $Gi^*(d)$ to verify if old building clusters exist, thereby enhancing the efficiency of urban mining.

This study provides valuable information on the quantity of resources in the anthroposphere for potential use. Due to the nature of urban ores, time is a priority consideration in HSA. The results of the correlation analysis could act as a reference for areas lacking information on MS, and the quantitative and high spatial resolution data could enhance management and planning in urban mining to facilitate economic transformation, leading to sustainable development.

2. Methods and data

In a micro-urban system, this study uses the total gross floor area (m^2) and the material intensity (kg/m^2) of the buildings in the district to quantify the total material stock (kg). The bottom-up MSA (Kleemann et al., 2017; Tanikawa et al., 2015; Tanikawa and Hashimoto, 2009) is expressed by Eq. (1). After the MS is quantified, this study combines the GIS data to get a high-resolution MS spatial distribution of the city. The steps of localization are explained as follows.