Resources, Conservation & Recycling 127 (2017) 168–178

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

Modeling material flows and stocks of the road network in the United States 1905–2015

Alessio Miatto[a,*], Heinz Schandl[b], Dominik Wiedenhofer[c], Fridolin Krausmann[c], Hiroki Tanikawa[a]

[a] Graduate School of Environmental Studies, Nagoya University, Japan
[b] Commonwealth Scientific and Industrial Research Organisation (CSIRO), Canberra, Australia
[c] Institute for Social Ecology (SEC), Alpen-Adria University, Klagenfurt, Austria

ARTICLE INFO

Keywords:
Dynamic MFA
Circular economy
Recycling
Material flow accounting
Roads
In-use stocks

ABSTRACT

Recent years have seen a growing interest in the potential for a more circular economy and the application of material flow accounting to increase knowledge on materials accumulating in in-use stocks. This study assesses the dynamics of stocks and flows related to road networks, which are a significant destination for recycled construction and demolition waste.

We develop a bottom-up stock-driven model to assess long-term inflows, outflows, and materials accumulated in roads to assess requirements for construction minerals of the road network in the United States. We estimate material requirements using the expansion of the transport network as a driver, and scheduled maintenance and technological coefficients from engineering literature to assess input and output flows. We apply the model to historical data for the United States road network from 1905 to 2015 and show that the current material stock of construction minerals in the road network of the United States is 15.1 billion tonnes, growing 21-fold since 1905.

During the 20th century, the material requirements of road construction have declined from 35% to 15% of economy-wide material consumption of non-metallic minerals in the United States. The share of roads in economy-wide in-use stocks has also declined from 17% to 13%. This shows that roads, once established, remain in place and most material flows are due to extending and refurbishing them, while the construction of completely new roads makes up a much smaller part of the material flows related to the road network.

1. Introduction

Construction minerals, including cement, bitumen, as well as sand and gravel, represent by far the largest fraction of all materials that are annually extracted and accumulate in buildings and various infrastructure as in-use stock (Krausmann et al., 2017). For many nations, they make up 50% of their domestic material consumption and up to 90% of material stock (Schandl et al., 2017). Their extraction and processing, especially of cement for concrete, is an energy-intensive activity and as a result the embodied greenhouse gas emissions of this material flow category are also significant (Müller et al., 2013).

Although non-metallic minerals such as cement, bitumen, sand and gravel are relatively benign environmentally, their sheer magnitude poses severe problems with local availability, transportation, land use change and landfilling of construction and demolition waste (Clark et al., 2006; Yoshida et al., 2016). To manage these materials and to improve recycling, it is essential to understand the magnitude of materials accumulated in buildings and transport infrastructure and to assess the dynamics of end-of-life flows to quantify the potential for recycling and for closing of loops (Haas et al., 2015; Wiedenhofer et al., 2015). Existing research has often focused on quantifying construction and demolition waste directly from on-site visits or via waste generation rates, while dynamic material flow approaches utilizing lifetimes have been much rarer (Wu et al., 2014). Recently methods were proposed to directly quantify in-use stocks accumulated within societies to allow investigation of the dynamics of material inputs and waste flows (see Augiseau and Barles, 2016 for a review). Assessing the recyclability of waste construction minerals (Pappu et al., 2007; Schiller et al., 2017), directly linked to in-use stock dynamics and input flows is hence an important step towards investigating the circular economy potential (Haas et al., 2015; Schiller et al., 2016).

Many studies on buildings stocks and flows are available (Augiseau and Barles, 2016), yet road networks tend to be under-investigated despite their quantitative relevance (Hashimoto et al., 2007, 2009;

* Corresponding author.
E-mail address: alessio.miatto@nagoya-u.jp (A. Miatto).

http://dx.doi.org/10.1016/j.resconrec.2017.08.024
Received 1 June 2017; Received in revised form 22 August 2017; Accepted 29 August 2017
Available online 27 September 2017
0921-3449/

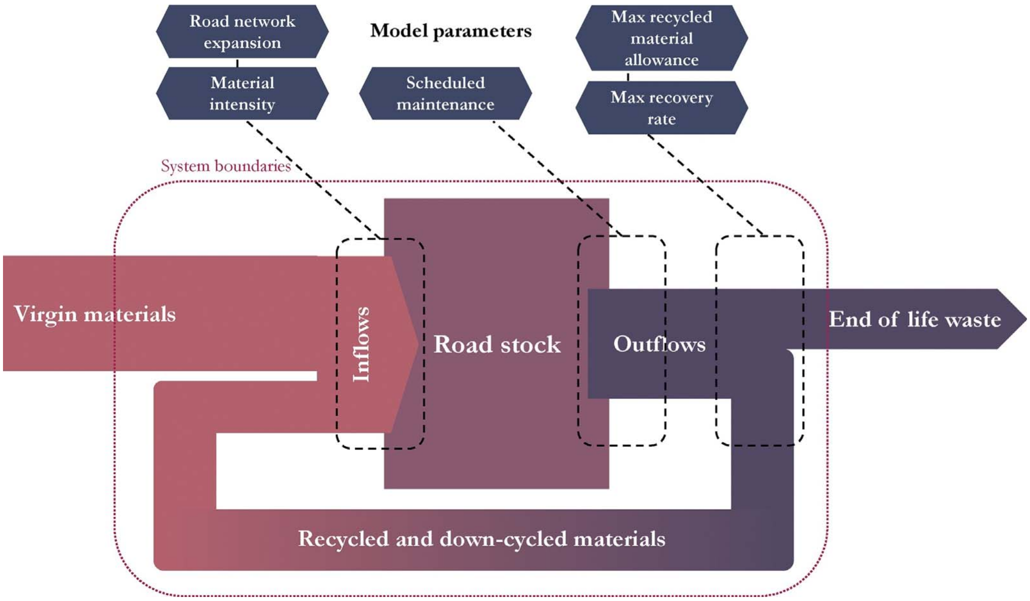

Fig. 1. Conceptual figure of the road material stocks and flows model.

Kapur et al., 2008, 2009; Schiller et al., 2016; Wiedenhofer et al., 2015), and researchers advocate the importance of focusing on civil and infrastructure networks (Wu et al., 2014). Some studies explicitly discern the stock of buildings and infrastructure, but do not provide information about related material flows; others calculate both stocks and flows, but limit their analysis to specific materials (Shi et al., 2012), while others estimate total material stocks and waste flows, but do not differentiate between buildings and roads (Fishman et al., 2014). So far, material stocks and flows for roads and residential buildings combined have been investigated for the European Union (Wiedenhofer et al., 2015), and for the United States for several types of stocks, but only for cement (Kapur et al., 2008). The main reason why available models that calculate stocks and flows cannot be directly applied to road infrastructure is the different nature of transport infrastructure compared to buildings. While buildings get renovated for many different reasons, and are eventually demolished, cases of actual road removal are extremely rare, and in most cases roads are "removed" simply by impeding vehicle access through gates or barriers (Switalski et al., 2004).

Buildings and roads are also very different with regard to where investment and operational spending comes from and in terms of ownership. Roads are usually common property, require public investment for building and maintenance and fall under different legislative control, depending on the type of road. They only generate an income if they are toll roads and operating models that include private ownership are the exception.

Roads also pose a difficulty for material flow accounting research because quantifying the materials required for the construction of roads and their maintenance is far from simple. Most studies so far have adopted rule-of-thumb accounting strategies based on a limited number of factors and often without specifically referring to changing technical construction standards over time; additionally, differences in road types and the specifics of road construction and renewal need to be taken into account. This study aims to improve the knowledge base about the material requirements of roads, the magnitude of material accumulated in roads, and waste flows from road refurbishment, specifically parametrized for the United States.

In this study, we design a stock-driven model that considers the specificities of different road types and historical changes in technical construction standards. We establish a bottom-up methodology to estimate physical stocks of roads, and derive the related material requirements for road construction and maintenance using best practice engineering knowledge and physical data about the extent of road networks. This methodology permits us to estimate the material composition of the road network over time, the quantity of materials needed for expansion, and maintenance and evolution in the ratio of the two. From this, we can estimate the potential of road construction to absorb road maintenance waste as well as building construction and demolition waste.

We apply this methodology to the United States of America, the country with the greatest extent of road network in the world (Central Intelligence Agency, 2013), for the years 1905–2015, to understand the material requirements to maintain in service what is by far the most common mean of transport in the United States (U.S. Department of Transportation, 2015a). For this purpose, we distinguish fourteen different road types and changes in technical construction standards over time. We intend to address the following questions: what is the size and composition of material stock of the US road network? What is the yearly requirement for virgin materials? What amounts of materials are recycled within the system? What is the yearly amount of waste flowing from road renewal? We relate the findings on material accumulation in roads to population, gross domestic product (GDP), and numbers of vehicles in circulation to gain a better understanding of the relationship between provisioning transport and mobility and the material underpinnings.

2. Methodology

2.1. Conceptual approach

While standard material flow accounts provide data on annual extraction and overall consumption of materials, they do not usually include information about the specific uses of materials in different economic activities (Fischer-Kowalski et al., 2011; UNEP, 2015). In order to determine which fraction of the national yearly consumption of nonmetallic minerals in the United States has been required to establish and maintain the road network we needed to develop an analytical approach which combined information about the evolution of the extent of the road network, of different road surfacing technologies, and of the material characteristics of these road types, to calculate overall inflows, accumulated material stocks, and outflows. This approach is operationalized in a model which is a bottom-up technology-based stock and flow representation of the material requirements of roads. The conceptual framework is schematized in Fig. 1.