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# Economic Growth and the Evolution of Material Cycles: An Analytical Framework Integrating Material Flow and Stock Indicators

Chao Zhang [a,d], Wei-Qiang Chen [b,e,*], Gang Liu [c], Da-Jian Zhu [a,d]

[a] School of Economics and Management, Tongji University, Shanghai 200092, China
[b] Key Lab of Urban Environment and Health, Institute of Urban Environment, Chinese Academy of Sciences, Xiamen, Fujian 361021, China
[c] SDU Life Cycle Engineering, Department of Chemical Engineering, Biotechnology, and Environmental Technology, University of Southern Denmark (SDU), 5230 Odense, Denmark
[d] Tongji University Sustainable Development and New-Type Urbanization Think Tank, Tongji University, Shanghai 200092, China
[e] Xiamen Key Lab of Urban Metabolism, Xiamen, 361021, China

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ABSTRACT

Understanding the relationship between material cycles and economic growth is essential for relieving environmental pressures associated with material extraction, production, and consumption. We developed an integrated analytical framework of dematerialization analysis incorporating both material flow and stock indicators. A four-quadrant diagram is designed to classify different stages of dematerialization based on the elasticity of material flow/stock to economic output or well-being. We then conducted a case study on the long-term evolution of aluminum cycle in the U.S., and found that different material flow and stock indicators decoupled from gross domestic product (GDP) growth in a clear sequential pattern. Flows closer to the beginning of the aluminum cycle (e.g., primary aluminum production) decoupled from GDP earlier than flows closer to the final consumption stage (e.g., consumption of final products). In-use stock of aluminum decoupled from GDP much more slowly than any flow indicator, and had just reached the status of relative decoupling around 2000. This phenomenon is determined by the fact that different causes of dematerialization, such as import substitution and secondary material recycling, take effect at different stages of economic development. Comprehensive understanding of dematerialization depends on in-depth analysis on material-economy relationships from an integrated stock and flow perspective.



## 1. Introduction

The process of modern urbanization and industrialization is a process of converting natural resources into a variety of man-made capitals to satisfy human needs by providing desired services. Man-made capitals continuously accumulate in the society in their physical forms, which construct the indispensable material base for all production and consumption activities (Graedel et al., 2015; Weisz et al., 2015). This process has been widely studied under the framework of socioeconomic metabolism (Fischer-Kowalski and Hüttler, 1998; Pauliuk et al., 2015). As world population and living standards increased rapidly since the middle of the twentieth century, the scale of societal material metabolism has also experienced tremendous expansion at the same period (Krausmann et al., 2009; Sverdrup et al., 2013), leading to increasing natural resource use and environmental pressures (Rockström et al., 2009; Steffen et al., 2015).

Understanding the relationship between material use and economic growth is essential for managing the societal material metabolism and realizing dematerialization. Studies in late 1980s and early 1990s (Bernardini and Galli, 1993; Considine, 1991; Ross et al., 1987; Williams and Larson, 1987; Auty, 1985) have shown that the long-term consumption of some bulk materials (e.g., steel, aluminum, cement) per dollar of gross national production (GNP), defined as intensity of use (IU), in some industrialized countries generally followed a bell-shaped curve. An appealing thought following these findings is the Environmental Kuznets Curve (EKC) for materials (Cleveland and Ruth, 1998; Bruyn and Opschoor, 1997; Stern, 2004), which assumes that IU of a certain material increases in the initial stage of development but tends to fall as income rises and economy matures.

After these early studies, economy-wide material flow analysis (EW-MFA) established a systemic and standardized framework for accounting aggregate material use of an economy (Ficher-Kowalski and Hüttler, 1998; Fischer-Kowalski et al., 2011; Weisz et al., 2007; Kovanda and Weinzettel, 2013; Muñoz et al., 2009; EUROSTAT, 2001). Extensive efforts have been devoted to developing multinational and global EW-MFA databases with transparent and comparable data (EUROSTAT, 2015; Krausmann et al., 2008; Krausmann et al., 2009; Schandl and Eisenmenger, 2006; Steinberger et al., 2010). Dematerialization analyses based on these datasets show decreasing trends of

* Corresponding author.
*E-mail address:* wqchen@iue.ac.cn (W.-Q. Chen).

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domestic material consumption (DMC) per unit of GDP for most developed economies (OECD, 2011). Two factors were claimed to result in the dematerialization trend, i.e., metabolic transition effect which shows biomass consumption intensity decreases fast during the industrialization process (Krausmann et al., 2008; Schaffartzik et al., 2014; Steinberger et al., 2010); and trade effect which shows developed countries shift raw material extraction and processing to developing countries (Dittrich and Bringezu, 2010; Dittrich et al., 2012).

EW-MFA focuses on the environmental pressures exerted by raw material extraction and biomass harvest, which are resource flows across the interfaces between nature environment and socioeconomic system. Since EW-MFA treats the socioeconomic system as a black box, details regarding how a certain kind of resource/material is transformed and used within the society are not revealed. Studies on material cycles, especially metal cycles, fill this gap by accounting both flows and stocks of a material in its all life cycle stages within a society, e.g., ore extraction, smelting, refining, fabrication, manufacturing, use, discard, recycle and reuse, etc.(Gordon et al., 2006; Graedel et al., 2015; Reck and Graedel, 2012; Reck et al., 2008; Chen and Graedel, 2012a; Cullen et al., 2012; Glöser et al., 2013; Reck et al., 2008). Static and dynamic material cycles for more than 50 elements have been constructed at national or global scales since the 1990s (Chen and Graedel, 2012a; Müller et al., 2014).

As more studies regarding material cycles became available, the relationships between material use and economic output have been investigated in more details. Graedel and Cao (2010) constructed composite indices for the flows of seven metals at four life stages covering 49 countries, and found that fabrication, use, and discard of metals are highly correlated to per capita GDP, while processing of metal ores has much weaker correlation. Liu and Müller (2013) integrated aluminum cycles of nations into the international trade network of aluminum products, and revealed that developed countries tend to play significant roles in deep processing of aluminum-containing products, while developing countries may be active in mining but not later stages after bauxite refining. Müller et al. (2011) presented the relationship between per capita iron stocks and per capita GDP for six industrialized countries and revealed a saturation pattern (S-shaped curve) of per capita in-use stock of iron. McMillan et al. (2010) quantified the in-use stocks of aluminum in the U.S. and found that the annual percentage change in GDP had a large and significant relationship with the annual percentage change in net additions to in-use stocks.

These findings suggest that conclusions regarding dematerialization may depend on particular material flow or stock indicators selected in the analysis. Different flows and stocks of materials may play very different roles in generating economic output. Without a clear definition of the indicators and a comprehensive understanding of interaction between material flows and stocks, any convenient dematerialization conclusion could be incomplete or even misleading. The purpose of this study is to establish a general analytical framework to investigate the long-term relationship between economic growth and the evolution of material cycles, incorporating both material flow indicators and material stock indicators. In Section 2, we propose a conceptual framework to interpret how flows and stocks of materials/products are complementary to each other in providing desired services and creating well-being through various economic activities. We argue that when studying the material-economy relationship, both flow indicators and stock indicators of material use should be included. Then a four-quadrant diagram comprising all possible relationships between material use (either flow-based or stock-based) and economic/well-being output is established in Section 3. We then illustrate this analytical framework with a case study of aluminum stocks and flows in the United States in Section 4.

## 2. Linking Material Flows and In-use Stocks to Economic Development and Human Well-being

Material flows and stocks are the most basic concepts in material cycle analysis. A given quantity of mass is considered stock if and only if the mass does not move across system boundaries during the entire time period of interest, otherwise, it is regarded as a flow (Gerst and Graedel, 2008). Particularly, in-use stock of a material is defined as the amount of the material within any final product that is used in society during the entire time period of interest (Gerst and Graedel, 2008). In-use stock of materials provides various functions or services satisfying human needs through in-use stocks of products containing those materials (Chen and Graedel, 2015), such as building infrastructures (Fishman et al., 2015; Müller, 2006; Tanikawa et al., 2015; Wiedenhofer et al., 2015) and durable consumer products (Chen and Graedel, 2015).

A conceptual framework illustrating how stocks and flows of materials/products are combined together in generating desired services to satisfy human needs and create well-being is presented in Fig. 1. Flows, stocks and processes in which flows are transformed, are represented by green hexagons, yellow squares and purple circles, respectively. Human society extracts or harvests virgin raw materials, e.g., metal ores, minerals, biomass and primary energy carriers, from the natural environment. These virgin raw materials go into the social-economic system to be transformed physically and chemically and manufactured into various products providing various services to satisfy human needs.

Economic activities can be classified into two kinds of basic processes: *production processes* and *service provision processes*. The production processes use materials (both virgin and secondary), labor and functioning of production facilities as inputs to produce products. The flow of labor is generated from the stock of human population, while the stock of existing industrial facilities provides functions enabling the production processes. These two inputs correspond to two factors of production, i.e., labor and capital, in the production function in economics. Production processes in modern industrialized society are highly complex and interconnected. It can be characterized as networks of material and product flows among industrial sectors in which raw materials are refined, fabricated, and manufactured into numerous semi (or intermediate) products and final products (Chen et al., 2016; Liu and Müller, 2013). As a result of globalization, such production networks are transforming from localized ones into global-wide supply chains, triggering transnational and teleconnected socioeconomic consequences, resource use and environmental impacts (Coe et al., 2008; Kagawa et al., 2015; Peters et al., 2011; Yu et al., 2013). This complex system is simplified as a single circle representing all production processes in Fig. 1, therefore *intermediate products* are "wrapped" in the circle.

*Final products* generated from the production processes can be classified into two broad categories according to their different roles in consumption: (1) durable products to be turned into physical stocks and (2) non-durable products providing services in flow forms. The first group of products comprises machinery, buildings, infrastructures and durable consumption goods. These products are also named as *capital goods* in economic terms. They are added to either stocks of production facilities or stocks of infrastructures and durable goods to replenish retired stocks as well as to increase the size of existing stocks. The second group of products includes non-durable consumption goods such as food, fuels, electricity and other consumables. These goods are not transformed into physical stocks, but rather dissipate or become wastes after providing services to consumers.

*Service provision processes* have direct linkages to human well-being. It is differentiated from the production processes in the way that it directly satisfies human needs, for example, nutrition, mobility, shelter, safety, sanitation, healthcare, communication, learning and recreation. It is the satisfaction of these various needs that generates and increases human well-being. The service provision processes also need three groups of inputs, i.e., (1) functions and services generated by stocks of infrastructures and durable goods; (2) non-durable consumption goods used during service provision; and (3) labor enabling the service provision. Service provision processes herein are different from the general concept of consumption in economics. Household consumption is