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Role of manufacturing towards achieving circular economy: The steel case

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ABSTRACT

Circular economy (CE) has been promoted worldwide as a strategy to reduce material use and to increase the material use efficiency by closing material loops at the societal level. The core concept of CE is to improve the circularity of material use through turning materials at the end of their service life into resources for others, however, there is very little information about the role of manufacturing in achieving CE. Using the concepts of dynamic material flow analysis and stock dynamics, this paper proposes a methodological approach to help understand the role of manufacturing in achieving CE. A number of other strategies such as material efficiency in conjunction with CE are also tested using the case of global steel use to draw conclusions.

1. Introduction

As resources become scarcer and associated impacts rise, the linear pattern of ‘take, make and dispose’ in industry and society calls for a change. In this context, circular economy (CE) has gained significant attention among global stakeholders including manufacturers [1–4]. The core concept of CE is to improve the circularity of material use (i.e. recycling, remanufacturing, reuse, etc.) through turning materials at the end of their service into resources for others [3,4]. Nevertheless, this End-of-Life (EoL)-based CE has been criticized recently on its the feasibility of implementation [5], cost competitiveness [6], rebound effect [2], effectiveness [7], etc. Hence, a holistic investigation is highly demanded.

Materials are essential for manufacturers to produce various products. Meanwhile, decisions from manufacturers regarding selection and use of materials in their corresponding activities strongly affect the way how the material is processed in its entire life cycle stages (i.e. production, manufacturing, use, and recycling). Over the past decades, manufacturers have developed and promoted various concepts (e.g. efficient manufacturing [8], eco-design [9], etc.) embodied in life cycle engineering (LCE) [10] to manage the corresponding products and materials from a life cycle perspective. Nevertheless, only limited LCE tools have been included to assist the CE. Herein, the Cradle to Cradle design framework proposed by Mcdonough and Mcdonough [4] is a perfect example which aims to design the product in a way that enables the waste in the EoL stage to become a resource for manufacturing of another product at the same or higher level (upcycling). However, from a broader systematic perspective, the contribution of manufacturers in achieving CE has not been well studied and appreciated. Hence, this study aims to reveal the critical role of manufacturers in achieving CE from a life-cycle based framework.

Such investigation requires a quantitative description and prediction on how materials are fed, processed, stored, and recycled inside the anthropogenic material cycle (AMC). Among all involved methods [10], the industrial ecology provides two well-established tools to serve this aim, i.e. dynamic material flow analysis (MFA), and stock dynamics. Herein, the dynamic MFA can systematically quantify the inflow, outflow, and loss of a given material in a process or system over some period [11] based on the mass balance principle. Stock dynamics helps to depict the mechanism in end-of-life material flow generation and explore drivers in the growth of material in-use stocks, defined as the sum of material in all included in-use products [12]. Dynamic MFA and stock dynamics have been combined as a powerful tool to predict the future global material stocks and flows in its anthropogenic cycle under different scenarios [12].

Iron and steel (henceforth described as steel) is selected as case study to explore the role of manufacturing in achieving CE. Steel is chosen because (a) it is the world’s most used metal for manufacturing of various products and (b) as a metal it can retain its utility after multiple runs of recycling and is acknowledged as the world most recycled metal [13]. Hence, with abundant studies available [6,14,15], this study can provide convincing results on how manufacturing contributes towards achieving CE, rendering the steel case a useful exemplary case for other materials in CE study.

2. Methodology

2.1. Life cycle framework

Implementation of circular economy can be monitored through the information of routes and magnitude of material in its

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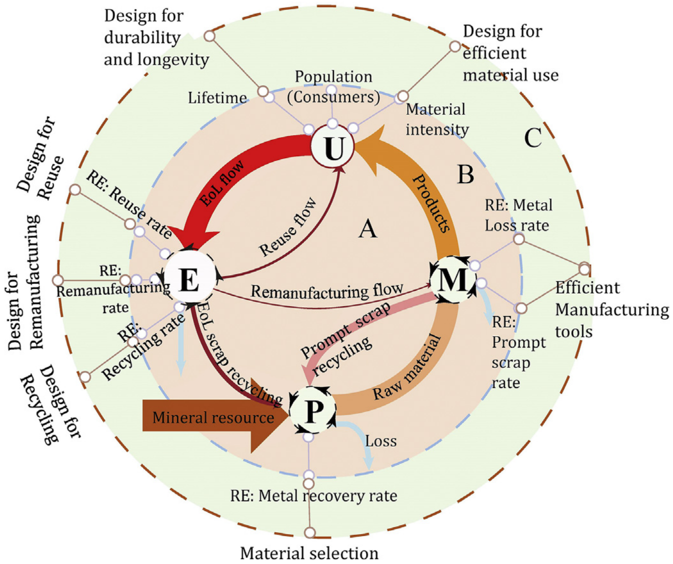

Fig. 1. Life cycle framework to link the LCE tools from manufacturers with material use in its anthropogenic cycle. (Note: P: material production stage; M: manufacturing stage; U: in-use stage; E: end-of-life stage; A: sub-system A; B: sub-system B; C: sub-system C.)

anthropogenic cycle. The corresponding decisions and activities (e.g. LCE tools) from manufacturers can have profound impacts on the entire life cycle stages, which includes but not limited to (a) determining the material flows and losses inside manufacturing, (b) selecting 'cleaner' material from more efficient producers, (c) improving the product design with less material use for same service and for durability and longevity; and (d) designing products for reusability, recyclability, and remanufacturing.

Therefore, a novel life cycle framework to link the LCE tools and AMC is shown in Fig. 1. Within the framework, three sub-systems are integrated. Sub-system A (the anthropogenic material cycle) is located at the center of this framework which presents the material stocks and flows along its life cycle. Sub-system B (material cycle indicators) comprises the major indicators in determining the material stocks and flows in the anthropogenic cycle. Sub-system C (LCE tools) is located at the outer ring of this framework, and some representative LCE tools are selected and allocated to each life cycle stage.

2.2. Dynamic material flow modeling

AMC is a key concept in industrial ecology with quantitative tools (e.g. MFA) [16] to depict the material stocks and flows in the anthropogenic cycle which includes four major life cycle stages: i.e. material production, manufacturing, in-use, and end-of-life. Apart from the linear flows from one stage to its following stage, four circular routes of scraps (i.e. prompt scrap recycling, reuse, remanufacturing, and recycling of EoL scrap) have also been captured in the framework. This study follows the basic dynamic MFA procedure [14,17]. For three of the life cycle stages (i.e. material production, manufacturing, and end-of-life), the mass-balance principle is applied to obtain the material inflow, outflow, and loss at the time t for stage k;

$$\begin{aligned} Outflow\,(k,t) &= Inflow\,(k,t) - loss\,(k,t) \\ &= Inflow\,(k,t) \times RE\,(k,t) \end{aligned} \tag{1}$$

The Eq. (1) can be solved for (a) *outflow* using production statistics (e.g. world steel yearbook) of each unit stage, (b) *inflow* using the mass balance with production statistics in the upstream and downstream unit stage, (c) *loss* using the mass balance of inflow and outflow, and (d) resource efficiency (*RE*) of this unit stage, defined as the mass ratio of outflow to inflow.

Meanwhile, for the in-use stage, its outflow is determined by using historical inflow to in-use stage and use lifetime of different products. The well-established lifetime distribution approach [14,17] is applied:

$$Outflow\,(t) = \int_{1900}^{t} Inflow\,(x) \times f\,(x,\tau,\omega)dx \tag{2}$$

where $f(x,\tau,\omega)$ is the probability densities of the lifetime distribution function (assumed to follow Weibull distribution [12] here), t is the lifetime of the product x, t is the current time, and ω is the lifetime distribution parameter. The detailed step-by-step calculation for each stage can be found in Refs. [11,15].

2.3. Depicting the impact of LCE tools on material flowanalysis

The overall study includes the historical quantification and future projection. The indicators shown in sub-system B of Fig. 1 are quite critical for this quantification as they determine the performance of the AMC [11]. There are 6 RE indicators that reflect the efficiency of LCE tools (metal recovery rate, recycling rate, etc.) and 3 in-use based indicators representing central aspects of the in-use stage (number of consumers, material intensity of the consumption and lifetime of products). For the historical quantification, values for those indicators are obtained directly from the mass ratio of outflow to inflow or statistics. As for the future projection, those indicators are exogenously given in scenario settings. More detailed scenarios are set based on the change of those indicators driven by the corresponding LCE tools. Moreover, the future projection is conducted with the well-established stock dynamics approach [14]. The final step is to compare the results in those scenarios with the basic scenario to gauge the impact of LCE tools in achieving CE.

3. Steel case and scenarios settings

Case study requires various input parameters (i.e. 6 RE indicators and 3 in-use based) as introduced in Section 2.3. For the historical quantification, the study directly adopted the results on historical material flows and stocks from previous work for the year 1900–2013 [11], in which those key indicators, and the historical demand and in-use stocks were obtained. For future projection, those input parameters are assumed in various scenario settings in Table 1, which involves three elements: population trend estimation, per capita material in-use stock growth, and changes in other key indicators as follows: (a) the future population is based on the medium scenario in “World Population Prospects” published by United Nations Population Division [18]. (b) The material intensity is allocated to the per capita basis using the per capita in-use stock as the proxy. The future trend of in-use growth is estimated based on the saturation hypothesis [17] which observed that most developed countries follow a similar saturation pattern of per capita in-use stock growth. The saturation level is around 13.4 tons steel per capita. Finally, (c) the changes in key RE indicators and lifetime of products are determined by the scenario settings.

Moreover, a product-specific treatment is applied to obtain more detailed results in three life cycle stages (i.e. manufacturing, in-use, and end-of-life), which are quantified based on four major categories of steel final products (i.e. construction, vehicles, machinery, and durable daily goods and others).

Table 1 gives the information of the specific scenarios and the settings of key indicators for the steel case allocated to each life cycle stage. This study applies two main scenarios, i.e. baseline scenario (BLS) and LCE scenario (LCES): BLS represents a business-as-usual estimation of future trends without additional policy intervention, and LCES includes the implementation of LCE tools to improve the material use along its full life cycle. To clarify the stage-specific impact of those LCE tools, seven sub-scenarios were proposed to integrate the LCES (as shown in Table 1). Based on detailed studies in Refs. [14,15,17], the current value and future potential values can be obtained for the steel case for most MFA indicators. With the attention and implementation of LCE tools, this study assumed that they can reach their full potentials