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A simulation methodology for a system of product life cycle systems

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ABSTRACT

To realize environmental sustainability, the flow of natural resources into industrial systems must be reduced and stabilized at a suitable level. One way to reduce resource flows in society is to establish resource-circulating manufacturing systems. To foster the circulation of resources in industry, life cycle simulation (LCS) technologies, which are based on discrete-event modeling, have been developed to dynamically evaluate the life cycles of products from resource extraction to end of life from both environmental and economic aspects. In reality, various industrial products interact with each other in unanticipated ways, and then these interactions affect the material flows in product life cycles. This type of complex system is called a system of systems (SoS). Focusing on this issue, we expand the evaluation's system boundary to include a system of multiple product life cycle systems. To handle an SoS quantitatively, we introduce typical types of interactions between product life cycle systems. The purpose of this study was to propose a new LCS methodology, called "LCS4SoS," that focuses on an SoS consisting of different kinds of product life cycle systems. A prototype system of LCS4SoS was implemented based on this proposed methodology. Through a case study, it was found that the proposed methodology is useful for evaluating an SoS consisting of multi-product life cycle systems.

1. Introduction

Environmental, social, and economic factors indicate that modern society is not sustainable in its present form [36,22,42,46]. Overcoming sustainability issues is a challenge, but doing so is crucial all around the world. For this reason, the United Nations has adopted the Sustainable Development Goals (SDGs) to meet by 2030 which aim to end poverty, protect the planet, and ensure prosperity for all [50]. From the viewpoint of environmental sustainability, including planetary limits, the situation is worsening [51,46]. For example, global resource extraction and use is accelerating, and the volume of international raw material trade is increasing [52]. To achieve environmental sustainability in terms of not only the improvement of eco-efficiency but also the absolute reduction of environmental impact, absolute sustainability is needed [25]. One potential effective way of achieving absolute environmental sustainability is to establish resource-circulating manufacturing systems.

A circular economy (CE) is a new economic concept focusing on the improvement of resource performance across the economy. A CE is anticipated as a solution to not only resource depletion but also economic problems such as the creation of jobs and new markets [14]. In line with this concept, the European Commission has adopted a new economic policy called the CE Package to help European businesses and consumers make the transition to a stronger and more circular economy where resources are used in a more sustainable way, such as by sharing, reusing, and recycling products [12]. The actions taken as part of the CE package are intended to contribute to "closing the loop" of whole product life cycles. Life cycle engineering (LCE) was introduced around a quarter of a century ago in order to address environmental sustainability in engineering [1,25]. LCE aims to maximize the total profit and reduce the environmental burden through life cycle thinking. Life cycle thinking takes the whole product life cycle into account, including resource extraction, production, usage, and the end of life (EOL) treatment. LCE is vital for achieving a CE.

The evaluation of a product life cycle is a critical factor in LCE. Therefore, methodologies and tools for life cycle assessment (LCA) [27,55] and life cycle simulation (LCS) [49,47,31] have been developed. A LCA is a methodology for accounting for the input of energy and materials and output of environmental burdens, such as carbon dioxide and water pollutants, statically throughout a product's life cycle. In contrast, LCS is a methodology for dynamic evaluation associated with production plans and collection projections, and is useful for cases of closed-loop manufacturing, including reuse and remanufacturing. Most reported LCA and LCS studies have focused on the life cycle system of an individual product or product family. However, modern engineering systems, including industrial products and social infrastructures, interact with each other in unexpected ways, resulting in increasingly complex systems [54]. In such cases, it is desirable to

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broaden the system boundaries for design and management. The concept of a system of systems (SoS) was proposed to gain understanding of the whole systems that emerge from such dynamic interactions among sub-systems [38], and various aspects of SoS are being studied [21,28]. However, an appropriate evaluation method for such complex systems based on life cycle thinking has not yet been established.

The purpose of this study is to propose a new LCS methodology, called "LCS4SoS," that focuses on an SoS consisting of different kinds of product life cycle systems. In Section 2, related works are reviewed and the issues to be solved are shown. In Section 3, the methodology of LCS4SoS is proposed, consisting of the framework, interaction types, and a simulation procedure. In Section 4, a prototyping system is implemented. In Section 5, a case study is carried out in order to verify the proposed methodology, referring to the example of mobility and battery systems. In Section 6, the significance and remaining issues are discussed, and finally, the paper is concluded in Section 7.

2. Related work

2.1. Concepts of a resource-circulating manufacturing system

Some resource-circulating manufacturing systems have already been proposed from an engineering standpoint. Fig. 1 shows the concepts of urban mining, industrial symbiosis, and closed-loop manufacturing, three types of resource-circulating manufacturing systems.

Urban mining may provide an alternative to mining virgin metals [23]. It is based on the concept that a large fraction of metal that is mined flows to cities, while the metal content of the rock being mined continues to decline. Urban mining is the largest-loop material circulation concept in social and economic systems related to the manufacturing industry (Fig. 1). However, urban mining has not been achieved because of various unresolved issues. The most difficult problem in urban mining is to establish a total urban mining business model consisting of multiple stakeholders. For instance, it is not clear who will lead the designing and operation of the business system. The private metal refining sector may be one candidate in terms of recycling technology. However, the governmental sector may be also a candidate in terms of national material security. It is also possible that the product manufacturing sector may be a candidate for leading the activity in terms of circular economy. Essentially, the problem is that these stakeholders have their own business models, which are basically independent of one another. Therefore, establishing a business model for an urban mining system must be discussed as a long-term, nationwide, multi-stakeholder issue.

Another resource-circulating manufacturing concept that has been proposed is industrial symbiosis [18,7,45,9,53]. Industrial symbiosis is a key concept in industrial ecology that focuses on the exchange of materials, energy, water, and by-products within the business networks in a local area. Many of the tools for industrial symbiosis aim to support the corresponding companies with respect to their input-output compatibility. However, industrial symbiosis does not help improve resource efficiency in terms of the whole product life cycle. It primarily helps in establishing a material network in the production processes of multiproduct life cycle systems for reducing waste emissions out of production systems. Currently, the leading player in industrial symbiosis is the process engineer. Industrial symbiosis is usually carried out under a contract among networked companies, and it takes effect under a constrained area.

Another concept, inverse manufacturing, which was proposed in the mid-1990s, aims to totally optimize a product life cycle and achieve closed-loop manufacturing [29]. The business models of film with lens and photocopier machines are well known as typical real-world examples of closed-loop business models. Business models are usually developed by product designers. However, the number of new examples of inverse manufacturing has yet to increase. One reason for this is that it is difficult to control and manage future uncertainty in a closed-loop business. Essentially, a business model of closed-loop manufacturing is profitable throughout collection, reuse, and remanufacturing after the EOL of products. Therefore, product life cycle planning for appropriate life cycle options, such as reuse and remanufacturing, is to be carried out in the early phase of product development [34].

If the product market and related technologies have changed significantly from the initial predictions, then the designed life cycle options cannot be executed, resulting in economic and environmental losses. For instance, it is likely that a closed-loop business model for a digital camera planned a decade ago would have failed, because the production volume of digital cameras assumed for reused components would have decreased due to mobile phones and camera functions embedded in smart devices. Furthermore, the product usage intensity and usage period cannot be controlled, resulting in a large amount of uncertainty in the remaining lifetime of a collected product or component. Lease and rental services are preferable for reuse businesses because they ensure product collection. Here, a reuse business is defined as a business model in which products are collected and reused [31]. However, launching a reuse business with a lease or rental service is not easy because the business risks are large [33]. A supposed closed-loop life cycle scenario is actually changed by interactions between a target-product system and related product systems or new technologies. An additional reason why inverse manufacturing businesses have not increased is because a manufacturing firm generally does not accept business cannibalization, which implies decreasing one's own new product sales by increasing reused or remanufactured product sales [24].

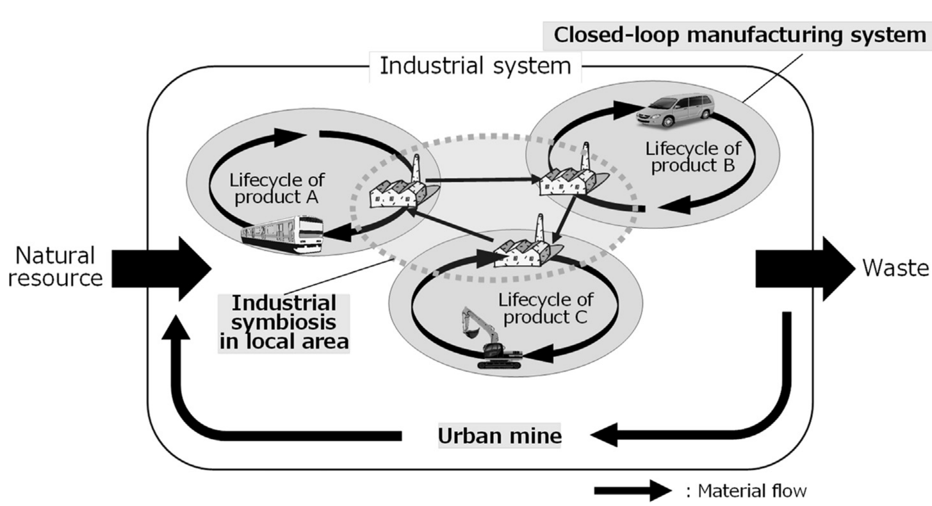

Fig. 1. Existing concepts of resource-circulating manufacturing systems.