A Framework of Stock-based System Design and Management toward a Steady-state Society

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Abstract

To ensure environmental sustainability, the flow of natural resource extraction must be reduced and stabilized at a suitable level. However, environmental sustainability and an infinitely growing economy are incompatible. To resolve this contradiction, a manufacturing system based on the idea of a sustainable steady-state society is proposed. In such a society, the value of stocks will be more important than that of flows. The purpose of this paper is to propose a framework of an approach for stock-based system design and management suitable for a steady-state society. The approach is supported by new life cycle simulation (LCS) technologies for dynamic handling of in-use stock, such as industrial products and systems. One is an LCS for system of systems that considers interactions among multiple models of the product life cycle. The other is a data assimilation LCS to modify internal data or LCS models based on real data acquired from the field. Concepts and preliminary studies of these LCS technologies show what can be expected for the proposed framework.

1 Introduction

Environmental, social, and economic factors indicate that modern society is not sustainable in its present form. The extraction of fossil fuels and minerals globally is already exceeding the environmental capacity. If environmental sustainability is to be achieved, then the flow of natural resource extraction must be reduced to a suitable level. However, the modern macro-economy is built on the premise of a potentially infinite economy. Under this premise, job security requires that the economy grow faster than per-capita productivity, and environmental sustainability requires that the resource productivity of the economy grow faster than the economy [1]. In practice, however, there is a physical limit to how much resource productivity can be increased. Thus, environmental sustainability and an infinitely growing economy are inconsistent with each other. To resolve this complex problem, we must fundamentally rethink our manufacturing system and maintain our artefact systems.

Here, alternatives, based on the idea of a sustainable steady-state society, are proposed. In economics, the concept of a steady-state economy was proposed by Daly [2], which was strongly influenced by Mill [3] and Georgescu-Roegen [4]. In sociology, Hiroi proposed a sustainable welfare society where the integration of welfare policy and environmental policy is essential [5]. The sustainable welfare society is based on the concept of the steady-state economy. In this study, a steady-state society is taken as a sustainable society modelled as a non-equilibrium quasi-steady-state system (Figure 1). In such a society, the value of stocks would be more important than that of flows, such as material flow and GDP, the net flow of natural resource extraction would be stabilized at an acceptable level, and all people would be able to access essential artefacts at an affordable price.

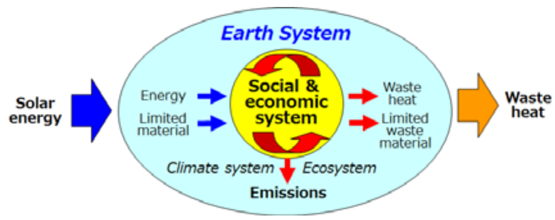

Figure 1: Schematic of a steady-state society

Generally, land, houses, and savings accounts are recognized as a stock in economics; however, industrial products and systems are regarded as in-use stock in this study. The purpose of this study is to propose a framework of system design and management suitable for a steady-state society, focusing on in-use stock. Related work and outstanding issues are summarized in Section 2. In Section 3, the framework and a research agenda for the stock-based approach are proposed. Preliminary studies on core simulation technologies for supporting the proposed approach are introduced in Section 4. Concluding remarks are provided in Section 5.

2 Related Work

2.1 Concepts of resource-efficient manufacturing

Urban mining is based on a 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 may provide an alternative to mining virgin metals [6]. Urban mining is the largest-loop material circulation concept related to the manufacturing industry. The size of in-use metal stocks and urban mining stock can be estimated by material flow analysis (MFA) at the national or regional level [7]. However, MFA cannot be used for designing and managing an artefact system at the product and business level.

Industrial symbiosis is a key concept in industrial ecology that focuses on the exchange of materials, energy, water, and by-products within business networks in the factory operation phase [8, 9]. To support these eco-industrial networks, MFA has been performed in industrial areas [9]. However, industrial symbiosis will not help improve resource-efficiency in the phases after manufacturing.

Inverse manufacturing is a concept in which resource consumption and total life cycle cost are reduced by focusing on reuse and maintenance rather than recycling [10]. This small-loop manufacturing system intends to increase resource-efficiency throughout product life cycle from mineral mining to landfill. However, the number of new examples of inverse manufacturing has not increased yet. One reason is that small-loop manufacturing systems are suitable for product families that have controllable post manufacturing processes. Although remanufacturing businesses led by third parties are promising compared with closed-loop businesses of an original equipment manufacturer, profitability is a priority rather than environmental gain. Also, demand for a remanufactured product in developing countries tends to decrease with economic growth of them.

2.2 Life cycle engineering

Life cycle engineering aims to maximize total profit and reduce environmental burden based on life cycle thinking. Thus it is an academic base of inverse manufacturing. A life cycle assessment (LCA) is used to quantify the environmental burden based on a typical static product life cycle under given scenarios. Consequential LCA (C-LCA) has also been proposed with an expanded system boundary for evaluating future scenarios [11]. In conventional LCA, namely, attribute LCA (A-LCA), one good is replaced directly with an equivalent quantity of another. However, demand substitution and the by-products of a process are considered in the calculation of C-LCA [11]. In C-LCA, consumption is usually changed indirectly by using an economic behaviour model, although there are exceptions.

To design circular manufacturing, product life cycle planning [12] and life cycle simulation (LCS) [13, 14] have been developed. An LCS is a core tool for estimating material flow and cash flow dynamically by using a discrete-event simulation technique. It is a powerful method for evaluating closed-loop business models, particularly for when the material flow changes dynamically. In principle, an LCS model is developed for one product family. LCS is not suitable for product life cycle management after sales because the information gap between the initial LCS estimate in the planning phase and the real product system behaviour in the operation phase increase.

2.3 System of systems

System of systems (SoS) is a developing field of system engineering. True SoS should be distinguished from large, complex, monolithic systems by the following five principal characteristics [15]: operational independence of the elements; managerial independence of the elements; evolutionary development; emergent behaviour; and geographic distribution.

Boardman et al. have also reported major features of SoS engineering, such as dynamic boundaries, emergent problems and continuous timeframes [16]. Because an SoS is a system, it has an objective to achieve, such as a national defence system [17] or a smart grid system [18]. However, the management framework of SoS is still under development.

2.4 Data assimilation

Decreasing the gap between simulation data and observation data is an essential issue for simulations. Data assimilation (DA) is a method for decreasing calculation error by merging observation data with estimates from simulation models [19]. DA is mainly used in earth sciences, for example, in meteorology in weather forecasting. Various DA methods, such as filtering and smoothing, are widely used and are selected according to the application.

3 Stock-based Approach

3.1 Assumption and position of this study

In this study, it is assumed that independent product life cycle systems configure an SoS when significant material, energy or informational interactions emerge between these systems. In this case, the objective of the SoS is assumed to be reducing and stabilizing material input flow into the SoS, although an individual product life cycle system has own objective such as maximizing life cycle profit.

There are two possible approaches to realizing a steady-state society (Figure 2). One is that the net flow of natural resource extraction could be stabilized at an acceptable level and quality of life is kept at a sufficient level. This approach is mainly applicable to developed countries where goods as in-use stock are diffused fully. In contrast, for developing countries, social infrastructure and durable goods could be diffused with lower resource consumption by a locally oriented approach [20]. The stock-based approach in this study intends to stabilize natural resource extraction.

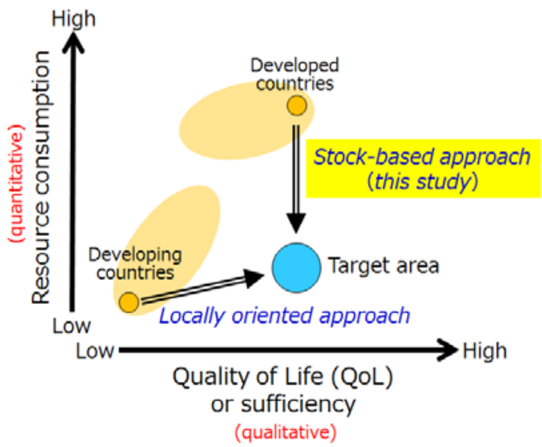

Figure 2: Position of this study

3.2 Framework

In general, uncertainty increases with the temporal and spatial expansion of problem. It is difficult to find a good design solution that reduces total material input of target product life cycle systems. In a real situation, it is impossible to design and launch all target products simultaneously. Then true integration of product life cycle design and management are expected for the above purpose. In stock-based approach, design and management are carried out recursively and continuously.

Figure 3 shows a schematic of the evolution of the stock-based approach. In most cases, individual product life cycle systems are designed, launched, and managed independently (t = 0). Products in the use phase are regarded as in-use stock in this study. Next, interactions among the life cycle systems appear, and an SoS consisting of the systems is generated (t = 1, 2). If the interactions disappear, the SoS also disappears. Thus, the system boundary of an SoS changes dynamically. The total resource inflow to the overall system boundary does not necessarily decrease at any time. It was evaluated whether the interactions decrease inflow of virgin resource or not. Here, appropriate interactions must be explored and selected continuously to reduce resource use over the long-term. Information about the interactions among the elements of the SoS is used to redesign the life cycle options of the elements. Here, life cycle option is defined as a way of resource-circulation of a product or component.

Interactions among product life cycle systems can be categorized into various types. The first type is demand substitution with an alternative product, in other words, a configuration change of in-use stock (I in Figure 4). This implies that sales or production of product A depend on the demand for product B. This type of interaction is relevant when total market capacity is a constraint and product share is the only business consideration. This interaction emerges between competitive products, for example, between gasoline and electric vehicles (EVs).

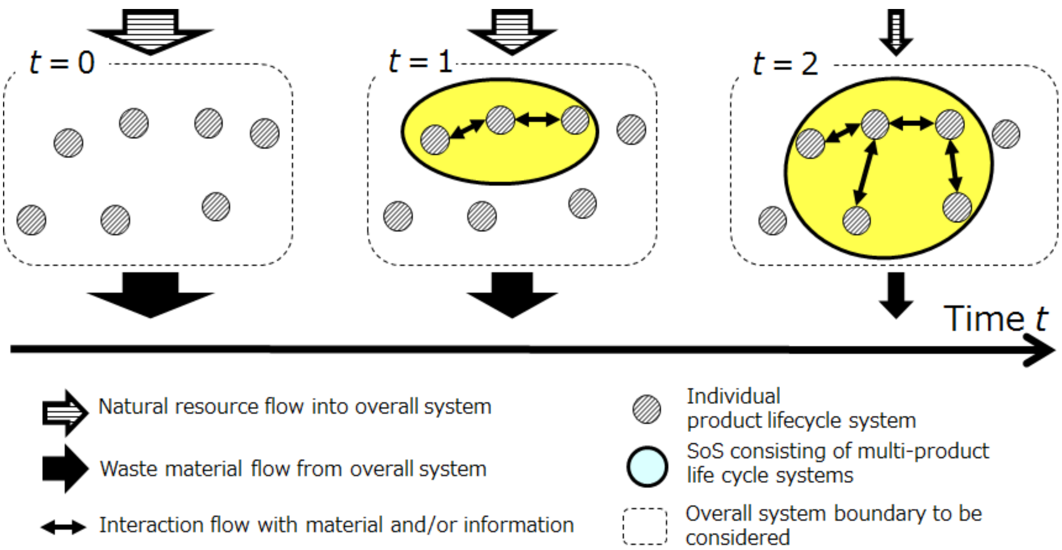

Figure 3: Evolution of interactions among product life cycle systems

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The second type is demand substitution by sub-function (II in Figure 4). This means that sales or production of product A depend on the usage of the sub-function of product B. For a high-grade multi-functional product, the sub-function itself sometimes affects other product sales. For instance, personal computers with high-quality displays may decrease sales of televisions for single households.

The third type is substitution of usage intensity of in-use stock (III in Figure 4). This means that the operation mode of product A depends on the use of the sub-function of product B. For example, for a multi-functional product, such as mobile information device, it may decreases the operation time of other information devices, such as internet televisions.

The fourth type is global reuse as other new or as new products (IV in Figure 4). Here, global reuse means that a used component or module is reused in a different product. A general purpose component could be used this way when it has a long remaining lifetime. Global reuse is a well-known life cycle option; however, it has not been analysed deeply.

The last type is global reuse for spare parts to prolong the lifetime of in-use stock (V in Figure 4). For example, a component from product B at the end of life is reused for maintenance of product C. In the context of the stock-based approach, this type of interaction is important to solve the problem of component suppliers discontinuing components.

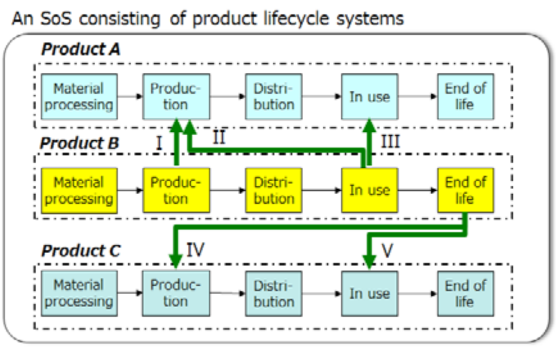

Figure 4: Interactions among product life cycle systems.

3.3 Research agenda

The research agenda for establishing a system design and management methodology based on the proposed framework can be summarized as follows.

1. Development of modelling and simulation methods for SoS consisting of independent product life cycle models. The interactions between product life cycle systems must be described to execute LCS consistently.
2. Development of a method to explore the interactions between product life cycle systems caused by external or internal factors dynamically.
3. Development of a method to find the most important interaction in order to reduce and stabilize resource inflow. Setting a temporal scale for this is also important.
4. Development of an automatic mechanism for decreasing the gap between estimated LCS data and real operation data to manage and design product life cycle systems recursively and continuously.

4 Preliminary Studies

4.1 LCS for SoS

We are developing a prototype system called LCS for SoS, which achieves the first requirement mentioned in Section 3.3. This system consists of an LCS module and management module for multi-LCS models [21]. In a case study, an LCS model of an SoS consisting of four kinds of product, namely, hybrid vehicles, EVs, gasoline vehicles, and home battery systems, was established. In the LCS model of SoS, some interactions among the LCS models were given, such as type I to IV described in Section 3.2. For instance, the interaction of type II and III between EVs and home battery systems decreases the EV battery lifetime and decreases sales of home battery systems, because an EV owner also uses it as an alternative home battery system.

Figure 5 shows the time evolution of monthly copper consumption over 20 years for 180,000 households. LCS for SoS and the aggregation of each LCS are different from each other, depending on whether there are interactions between LCS models. In this example, the interactions cause a negative environmental effect, namely, an increase of overall copper consumption. This is because the EV battery degradation is accelerated by its alternative use as a home battery system,

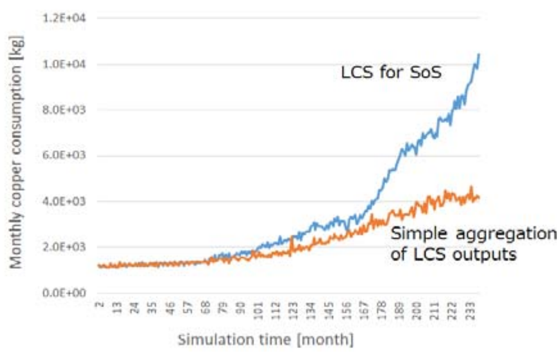

Figure 5: Simulation example for monthly copper consumption

although copper consumption is decreased by the decrease in sales of home battery systems.

This preliminary study suggests that we can explore appropriate interactions between different kinds of product life cycle systems to reduce total resource consumption. In future work, a support method for setting an interaction between product life cycle systems in LCS for SoS will be developed, and geographical data will be applied to LCS for SoS.

4.2 Data assimilation LCS

To achieve the fourth requirement in Section 3.2, a data assimilation LCS (DA-LCS) system is being developed that revises the initial LCS model continuously by using real measurement data (Figure 6). A prototype system of DA-LCS consists of an LCS module and a DA module [22]. This system allows the LCS model to be modified by data analysis at appropriate intervals, and replaces the initial LCS data with real data retrospectively. In a case study of reusing solar photovoltaic panels, it was shown that the LCS model and data can be modified and replaced automatically. Consequently, the estimate error of DA-LCS is less than that of the initial LCS. Future work will include developing guidelines for setting suitable DA conditions such as the DA interval.

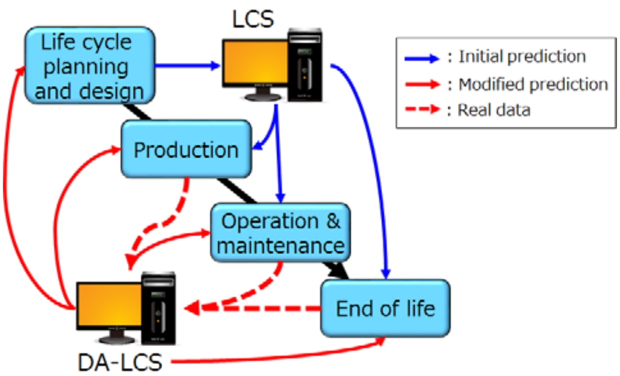

Figure 6: Schematic of DA-LCS

5 Concluding Remarks

In this paper, a framework of stock-based system design and management was proposed to realize the steady-state society. The proposed approach aims to manage and design the interactions between in-use stocks continuously. Preliminary studies of core simulation tools were shown that suggested that engineering support for the stock-based approach can be expected.

This study was inspired by the concepts of the steady-state economy and society from the fields of economics and sociology. This study provides an engineering approach to the steady-state society, if it is accepted widely as alternative to the current infinitely growing economy.

The details of the LCS for SoS and DA-LCS will be reported elsewhere.

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