Available online at www.sciencedirect.com
ScienceDirect
Procedia CIRP 61 (2017) 110 – 115
www.elsevier.com/locate/procedia

The 24th CIRP Conference on Life Cycle Engineering

A functional approach to life cycle simulation for system of systems

Kazune Kawakami[a,*], Shinichi Fukushige[a], Hideki Kobayashi[a]

[a] *Department of Mechanical Engineering, Osaka University, Yamada-oka 2-1, Suita, Osaka, 565-0871, Japan*

* Corresponding author. Tel.: +81-6-6879-4224 ; Fax: +81-6-6879-7262. *E-mail address:* kawakami@ssd.mech.eng.osaka-u.ac.jp

Abstract

Life cycle simulation (LCS) evaluates dynamic material flows in the life cycles of a single product family. However, in reality, there are various interactions between different product life cycles, such as demand substitution among different types of products and the global reuse of components in other products. In this paper, an entire system consisting of multi-kind product life cycles is regarded as a system of systems (SoS), which is an assemblage of systems where each system possesses operational and managerial independence. This paper proposes an LCS system for SoS that will support engineers in making decisions about system management through describing and simulating interactions.

Keywords: life cycle simulation; system of systems; function model

1. Introduction

As a response to global environmental problems in the manufacturing industry, a substantial reduction of resource flow and its stabilization to an acceptable range are necessary for sustainable manufacturing. The concept of a circular economy is an effective response to these requirements [1]. Resource circulation is expected to make the resource flows of the Earth's limited resources sustainable while minimizing the effect on the environment and creating more value with less input.

Life cycle simulation (LCS) is a useful method for establishing the circular economy from the perspective of life cycle engineering. The method evaluates the performance of product life cycles for holistic design [2, 3]. LCS is mainly applied to analyzing dynamic resource flows, including recovery loops such as reuse, remanufacturing, and recycling in a product life cycle.

In some situations, material and information flows appear between multiple product life cycle systems. In other words, product life cycles could interact with each other by, for example, component reuse in another type of product. Traditional LCS studies typically deal with a single product family. To establish the circular economy, product life cycles should be designed and managed, including the interactions among them, over the long term. To introduce such interactions into an LCS model, it is necessary to develop a new modeling and simulation system.

To reduce total resource consumption, an LCS system is required for evaluating the system of systems (SoS), which consists of multi-kind product life cycles. In this study, we develop an LCS system for SoS that models and simulates interactions between multi-kind product life cycle systems in an SoS. In this paper, we assume that the interactions appear between products that have similar functions. The main focus of this paper is to propose a functional approach by using a function tree to find candidate interactions.

2. Related works

2.1. Evaluation of resource flow

For evaluating the resource flow, many methods have been proposed. For example, material flow analysis (MFA) is a systematic method for evaluating the flows and stocks of materials [4]. MFA has been widely applied in policy design of resource and waste management. The method has also been applied to analysis of regional and policy-wide areas. In contrast, life cycle assessment (LCA) is an evaluation methodology for a whole product life cycle [5]. Traditional

doi:10.1016/j.procir.2016.11.255

LCA evaluates a typical static product life cycle system., whereas consequential LCA aims to describe how environmentally relevant flows will change in response to possible decisions [6], and can evaluate indirect environment impacts caused by changing the product life cycle. However, these LCA methods cannot evaluate dynamics in the material balance of a product life cycle, particularly when the product life cycle has loops, such as with reuse and recycling.

LCS calculates material flows and cash flows dynamically based on a discrete event simulation technique [2, 3]. It can simulate the physical and functional deterioration of individual products at consumer sites as well as the execution of technical services such as maintenance, upgrade, remanufacturing, reuse, and recycling. There are some examples of parts reuse between different products as remanufacturing [7]. A study of remanufacturing has evaluated its environmental and economic effects and mentions the importance of considering demand substitution [8].

2.2. SoS

The concept of SoS has been developed in the field of system engineering. An SoS is an assemblage of constituent systems and is distinguished from large, complex, monolithic systems by five characteristics: operational independence of the elements, managerial independence of the elements, evolutional development, emergent behavior, and geographic distribution [9]. Although there are some approaches to addressing SoS, such as smart grids [10], the framework is still under development.

2.3. Function modeling

A function is an abstract formulation describing the role of a product. An overall function of a product can often be divided into identifiable sub-functions [11]. Function modeling is the development of models of products based on their functionalities [12]. It is a key step in the product design process. A product model for functionality is called a function model. It allows us to understand a product's overall function as a set of sub-functions while showing their connectivity [13].

3. LCS for SoS

We propose a new LCS system for an SoS to help engineers to describe interactions between product life cycle systems. We call this LCS "LCS for SoS." The LCS system is developed based on a life cycle model as a component of the SoS. Here, the life cycle model consists of three sub-models: a life cycle flow model, structure model, and a function model. The relationships between functional elements in the function model and the physical components in the structure model are represented by the connection link structure in the life cycle model.

We assume that the LCS for SoS is used at the design and management stages in the product life cycle. In response to the temporal changes in interactions that appear during operation of the artifact systems, the system supports decision making to choose the best re-design and management pattern.

We assume that interactions might appear between product life cycle systems with similar functions. For example, it is expected that the demand for electric vehicles (EVs) will substitute the demand for gasoline vehicles (GVs) because they have similar functions. Therefore, the functionality model provides support in defining an appropriate interaction.

3.1. Interactions among product life cycles

In designing an SoS, interactions among product life cycle systems in the SoS are defined. The objective of the SoS design in this study is to reduce and stabilize resource consumption in the system overall, although an individual product life cycle system in the SoS aims to maximize the profit. Each system has interactions between material flows and the design of appropriate interactions may reduce the resource consumption in the entire SoS.

Considering the variety of interactions, Kobayashi categorized the interactions among product life cycle systems into the following five types (Fig. 1) [14].

I. Demand substitution with an alternative product
   Sales or production of product A depends on the demand for product B. This interaction emerges between competitive products, and it is relevant when total market capacity is a constraint and product share is the only business consideration.
II. Demand substitution by sub-function
   Sales or production of product A depends on the use of the sub-function of product B. For a high-grade multi-functional product, its sub-function sometimes affects other products.
III. Substitution of usage intensity of in-use stock
   In–use stock means existing products in the use phase. This interaction means that the operation mode of product A depends on the use of the sub-function of product B.
IV. Global reuse as other new or as new products
   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.
V. Global reuse as spare parts to prolong the lifetime of in-use stock
   A component from product B at the end of life is reused for maintenance of product C.

In this paper, we use this categorization of interactions in making life cycle models for SoS. We focus on functionality of products as a method to seek these interactions.

3.2. Functional approach to exploring interactions

To handle the variety of products created by different engineers, it is important that their functions are described