Simulating Life Cycles of Individual Products for Life Cycle Design

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Abstract

Minimizing environmental loads and resource consumption is a major issue in the manufacturing industry while enhancing value of products. Individual products have a variety of states depending on their life cycle histories even if they are produced from the same design information. While design information represents their ‘nominal information’ specified by designers, we call a specific state of an individual product as ‘entity information.’ The differences in individual products make it instable in terms of the states and quantity to circulate resources and to deliver service activities at the after sales market. To realize efficient resource circulation and high quality services, designers should determine nominal information of a product and of its life cycle flow by analyzing the entity information at its design stage. This paper proposes a method for modeling both nominal information of a product life cycle and the entity information. This method represents the nominal information with product model and life cycle flow model. In this paper, we define a model of the entity information, which shows states of individual products and the number of the products in each life cycle process such as maintenance, collection, and end-of-life treatments. To create this model, we derive entity information throughout the entire life cycle flow by using life cycle simulation technique. A case study of a smart phone is illustrated for demonstrating the feasibility of the proposed modeling method.

Keywords: life cycle design; resource efficiency; life cycle simulation; CAD

1. Introduction

Minimizing environmental loads and resource consumption is a major issue in the manufacturing industry while enhancing value of products throughout their life cycles. In recent years, European countries have been highlighting how to utilize resources efficiently according to Resource Efficiency Roadmaps [1]. To cope with these issues, life cycle design (LC design) is a promising approach, which designs a product and its life cycle flow (i.e., network of life cycle processes such as not only manufacturing and use but also maintenance, disassembly, end-of-life treatments, and so forth) in an integrated manner [2].

A product life cycle includes ‘entities’ such as products, parts, and materials. Individual entities have a variety of life cycle histories even if they are produced from the same design information. The differences in entities make it instable in terms of their states and quantity to circulate resources (e.g., recycling, reuse, remanufacturing, and so forth) and it may result in the increase of the costs to deliver service activities at the after sales market. Therefore modeling the different life cycle histories of the entities is a key aspect for LC design on determining how to circulate resources and how to manage maintenance and other service activities. For example, if the parts designers intended to reuse are more deteriorated than expected, the resources and the costs consumed for the reuse design become in vain.

For supporting LC design by solving this issue, this paper proposes a method for modeling a product life cycle by simulating life cycles of entities at its design stage. In this paper, we call the specific state of each entity as ‘entity information,’ while design information represents its ‘nominal information’ (i.e., the designed and intended dimension, tolerance, material, and so forth) specified by designers.
2. Nominal information and entity information in life cycle design

2.1. Issues on modeling a product life cycle

Some researchers (e.g., [3][4]) have discussed that the state (or condition and quality) and quantity of products is an important factor for circulating resources efficiently. Differences in the states of returned products are much larger than the differences in raw material and new parts [5]. The number of entities in each life cycle process varies along time. The change of the quantity depends on circulation timing and circulation path of entities. There are several existing studies for estimating the number of returned products (e.g., [4][6]).

The state and quantity of entities are also regarded as important factors for managing maintenance and other service activities. This is because the differences in the states of entities, for example, make operation time instable (e.g., disassembly time of each entity depends on how seriously its screws rust) and make operation process in a service activity different (e.g., replacing one part or overhauling). The change of the quantity, for example, makes frequency of maintenance and service activities in each month different.

Since most of the total costs throughout a product life cycle is determined at the early design stage [7], designers should determine nominal information of the product life cycle by analyzing the state and quantity of entities for circulating resources efficiently and for delivering service activities in high quality. Few studies, however, have focused on establishing a framework for modeling both of the nominal and entity information of a product life cycle at LC design stage. Several research areas have represented a product life cycle. For example, life cycle assessment represents a product life cycle as a set of life cycle processes of a product (e.g., [8]). n-LC Model consists of Hierarchical Product Structure Model and LC Flow Model. Hierarchical Product Structure Model represents structure and attributes of a product by nodes and links. A node, which we call ‘Entity Node,’ indicates a product, a part, and material. Entity Node possesses name, part number, as well as attributes such as geometry, constituent material, and weight. To represent its geometry as an attribute, each Entity Node has a reference path to a 3D solid model. A link is classified into three types: hierarchy, connection, and transformation. A hierarchy link denotes that a parent node is an aggregate of its child nodes. A connection link denotes connection among parts such as fix connection, motion constraint, and power transmission. Transformation link denotes a state transition between Entity Nodes.

LC Flow Model represents a network of life cycle processes by nodes and links. A node, which we call ‘LC Process Node,’ possesses given parameters, input parameters, output parameters, and a procedure. A procedure describes behavior of the life cycle process. A link, which we call ‘Flow Link,’ represents a flow of products, parts, materials, money, and information between life cycle processes.

We also defined an integration scheme for Hierarchical Product Structure Model and LC Flow Model. This scheme connects Entity Nodes and Flow Links and represents which factors. It is important to analyze which differentiating factor causes the differences in the states and the changes of the quantity for realizing the efficient resource circulation and the high quality services. As the first step for supporting the analysis at the design stage, this study proposes a method that enables to model a product life cycle by relating the nominal and entity information. For this purpose, this study represents differentiating factors in n-LC Model and simulates the entity information from the n-LC Model by using life cycle simulation (LCS) technique [9].

3. Design object model for life cycle design focusing on the entity information

3.1. Nominal information model of a product life cycle

This section briefly describes n-LC Model, which we have proposed in the previous work [2]. n-LC Model consists of two sub-models: Hierarchical Product Structure Model and LC Flow Model. Hierarchical Product Structure Model represents structure and attributes of a product by nodes and links. A node, which we call ‘Entity Node,’ indicates a product, a part, and material. Entity Node possesses name, part number, as well as attributes such as geometry, constituent material, and weight. To represent its geometry as an attribute, each Entity Node has a reference path to a 3D solid model. A link is classified into three types: hierarchy, connection, and transformation. A hierarchy link denotes that a parent node is an aggregate of its child nodes. A connection link denotes connection among parts such as fix connection, motion constraint, and power transmission. Transformation link denotes a state transition between Entity Nodes.

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part of the product passes through which life cycle process, as shown in Fig. 2.

3.2. Entity Information model

Entity Information Model stores entity information $ei$, which we define as follows:

$$ ei = (eid, ni, t, lcp, s, assy) $$

(1)

$eid$ is identification number of an entity. $ni$ is its referring nominal information and possesses a path to an Entity Node as its value. $t$ is a specific time when the entity exists. $lcp$ is a life cycle process where the entity locates at time $t$. $s$ is state of the entity as a set of its attributes at time $t$. $assy$ is a set of sub-entities that constitute the target entity.

3.3. Representing relationship between the nominal information and the entity information

In order to enable designers to analyze which differentiating factor causes the differences in the states of entities and the changes of quantity, we take two approaches.

First, this paper classifies differentiating factors into two types: physical behavior of entities and differences in life cycle processes. As for a physical behavior, entities treated in the same way under the same operating environment may have different states. For instance, if a user keeps two products that have originally the same states, one of them goes wrong after specific time while the other goes well. An example of the physical behavior is failure rate. This study represents a physical behavior as an attribute of an Entity Node. As for differences in life cycle processes, for example, how often users operate their products makes deterioration of each product different. This study represents a difference in a life cycle process in a procedure describing how to treat entities as a function of attributive value of an Entity Node related to the LC Process Node, based on the integration scheme for Hierarchical Product Structure Model and LC Flow Model.

Second, this study creates Entity Information Model by running LCS with n-LC Model as its input. LCS [9] dynamically simulates flows of products, parts, materials, money, and information throughout the entire life cycle flow based on a discrete event simulation technique. During its simulation period, LCS stores the entity information $ei$ in each life cycle process at each time in Entity Information Model.

4. The role of Entity Information Model for supporting through-life engineering services

This section illustrates the role of the model proposed in Section 3 for designing a product life cycle with service activities in high quality at the after sales market.

Entity Information Model represents the entity information, which describes both differences in states and number of the entities at a specific time in each process. This representation supports service operators for managing maintenance and other service activities, since the quality of the operation depends on the instability of states and quantity of entities, as described in Section 2.1. There are several existing studies for managing maintenance from the viewpoint of states and quantity of products (e.g., [10]). However, it is difficult for these research efforts to improve the quality of the maintenance and other service activities by changing the nominal information of the product since they do not focus on its design stage but the maintenance stage (i.e., after the product design stage). On the other hand, our method proposed in Section 3 represents both the nominal and entity information of a product life cycle by relating n-LC Model and Entity Information Model. This supports a designer for controlling the states and quantity of the entities in the target life cycle process at the design stage by modifying nominal information of both a product and its life cycle flow so as to achieve their goals on the service activities. For example, a service designer can determine the capacity of facility and manage the number of workers to hire for their maintenance operation by analyzing the states of used products in the market at each month and the quantity of the products with Entity Information Model.

A key issue on delivering high quality services is modeling a product life cycle even after its design stage. This is because a product life cycle has long period from its design and manufacturing through usage to collection and end-of-life treatments. During the period, by collecting the information from real-life products such as use history of products and the degree of their deterioration, not only the gap between the information modeled with n-LC Model and the real-life information but also the gap between Entity Information Model at the design stage and the real-life information will be revealed. There are two key aspects for analyzing the gap for more real modeling of the product life cycle: differentiating factors and life cycle histories. Real-life information about differentiating factors (e.g., how long users use their product per a day) can be directly used as the nominal information on the n-LC Model. Real-life information about life cycle histories of entities (e.g., how deteriorate a product is) can be used indirectly by identifying which differentiating factors have possibility to cause the gap between the real-life information and the entity information modeled at the design stage. To collect and manage such real-life information, Product Life cycle Management (PLM) (e.g., [11]) and other technology such as Internet of Things (IoT) [12] has been highlighted in recent years.

5. Case study

This section illustrates a case study demonstrating the efficiency of the proposed modeling method. In this case study, we modeled a product life cycle of a smart phone.

5.1. Modeling nominal information of a product life cycle and simulating the entity information

While the current product life cycles of smart phones in Japan mainly incorporate material recycling [13], this case study modeled a product life cycle with parts reuse to the smart phone in the next generation to realize more efficient resource circulation. With the proposed method, we aimed to design a product life cycle that achieves "reuse rate more than
“maintaining total benefit for manufactures same as that of the current product life cycle.” We selected Center Panel as a reuse part. Center Panel holds a display, a print circuited board, and a battery and is made of polycarbonate and several other materials that make recycling difficult.

We modeled the nominal information with n-LC Model as shown in Fig. 2 and set differentiating factors to the n-LC Model. Examples of differentiating factors are shown in Table 1. As a differentiating factor, for example, we defined that Charpy impact strength $cis$ [J/m] of Center Panel deteriorates as follows:

$$cis = -\alpha \times \frac{uf}{uf_s} \times t + cis_0$$

where $uf$ is usage time of Standard User, $uf_s$ is usage time of users of each individual smart phone, $cis_0$ is the initial value of Charpy impact strength of Center Panel. We defined $cis_0$ as follows:

$$cis_0 = cis_{pc} \times th$$

where $cis_{pc}$ is impact strength of polycarbonate and $th$ is thickness of Center Panel. $cis_{pc}$ is evaluated by Charpy impact test, which determines the brittleness or toughness of specimens by striking a specimen with a controlled weight swung from a set height [16]. We set $cis_{pc}$ as 80.0 [KJ/m²] based on [17] and $th$ as 1.00*10⁻³ [m] based on tear-down of Galaxy sII.

$$cis = \alpha \times \frac{uf}{uf_s} \times (t + cis_0)$$

$D$ in Equation (2) is rate of change in the Charpy impact strength to time duration. We set the rate as 0.67 [J/m²/month] by assuming that the Charpy impact strength decreases linearly and becomes zero after Standard Users use their smart phones in ten years. $t$ is duration time in the product life cycle.

We set the simulation time to 60 month as a sufficient period for all users to dispose of their first generation of the smart phones. We created Entity Information Model by running LCS with the n-LC Model. With the Entity Information Model, we described differences in states of entities and changes of their quantity throughout the entire life cycle flow. For example, Fig. 3 (a) indicates time changes in the number of assembled and collected smart phones. Fig. 3 (b) indicates Charpy impact strength of Center Panels shipped from Disassembly process, with the number of the entities accumulated from 1st to 60th month. The colors of bar graph in Fig. 3 (a) and (b) depict the collected turn.

### 5.2. Design change

The result of the simulation indicates that the product life cycle was 8.59% of reuse rate of Center Panels and total benefit for manufacturers was 99.2% of the current product life cycle. That is, reuse rate of the product life cycle is far from its objective value. The Entity Information Model in Fig. 3 (a) indicates that the number of collected smart phones was much smaller than the number of the manufactured second generation of the smart phones. We judged that one of the
The case study succeeded in representing the differences in the states of individual smart phones and the changes of the number of assembled smart phones of the second generation of collected smart phones of the first generation and the Panel more than 35%. One is imbalance between the number of assembled smart phones of the first generation and the number of returned used smart phones). We set collection rate from 50% to 80% and ran LCS with every 10%. Here, we assumed the collection rate much higher than actual data [13] in order to identify its minimum requirements for realizing the reuse business.

The simulation result showed that while total benefit for manufactures was more than the current product life cycle, the reuse rate was 29.34% in maximum under the condition of the collection rate 80%. By analyzing the differences in states of Center Panels in Entity Information Model (see Fig. 4), we found out a solution to increase Charpy impact strength of Center Panels because some of the returned Center Panels were not reusable due to low Charpy impact strength. Since the Charpy impact strength depends on material and thickness of Center Panel as shown in Equation (2), we decided to increase the thickness of Center Panel in this case study.

We evaluated the product life cycle with the thickness of Center Panel from 1.00 [mm] to 2.00 [mm] under the condition of the collection rate 80%. As a result, the product life cycle with thickness of 1.15 [mm] achieved 35.11% of reuse rate and 102.0% of total benefits for manufacturers to the current product life cycle and was minimum additional resources for this design change. Lastly, we verified the feasibility of the design change by adopting the thickness of Center Panel to a 3D solid model.

6. Discussion

The case study succeeded in representing the differences in the states of individual smart phones and the changes of the quantity in each life cycle process by the proposed method. This representation supported us for finding out problems on circulating resources efficiently. For example, we found out two problems to be resolved for achieving reuse rate of Center Panel more than 35%. One is imbalance between the number of collected smart phones of the first generation and the number of assembled smart phones of the second generation as shown in Fig. 3 (a), and the other is differences in the Charpy impact strength of Center Panels as shown in Fig. 4. In addition, we identified which differentiating factors cause the problem by life cycle histories of target entities represented by Entity Information Model and its relationship with n-LC Model. For example, as the cause of the low reuse rate, we selected at first the collection rate, which is a differentiating factor that makes life cycles of Center Panels different and then selected the Charpy impact strength of the Center Panel, which relates to reusability of Center Panels. For identifying the cause, however, designers need to find out by themselves which differentiating factors in n-LC Model is critical for resolving the problem.

Since the proposed model includes both the nominal information of a product life cycle and the entity information, it enabled us to evaluate the feasibility of the geometry of the product after finding and adapting the solution in Section 5 for increasing reuse rate to n-LC Model. This means that the proposed method supports designers for detailing the nominal information of a product life cycle and simulating the entity information, in order to find out the best design solution.

In the case study discussed in Section 5, we focused on resource circulation of a smart phone with parts reuse. A service operator can also utilize the modeled product life cycle for managing their maintenance activity. For example, since a Battery is a key part for making life span of smart phones longer [14], managing its maintenance (e.g., upgrading the battery for free) may increase the value of smart phones throughout their life cycles. In this case, however, the reuse rate of Center Panel will decrease due to the longer life span of smart phones. One solution for this trade-off problem may be parts reuse into third generation of the smartphone. But this is not easy because the shape and size of the smartphone will be different between the first and third generations. Therefore a LC designer and a service operator need to determine the nominal information of the smartphones across multi-generations by balancing between maintenance and reuse activities so as to realizing both efficient resource circulation and high quality service at the after sales market. The proposed model supports for determining such nominal information of a product life cycle by simulating the entity information.

7. Conclusion

Differences in the states and quantity of entities make it instable to circulate resources and to deliver service activities at the after sales market. To realize a product life cycle with the efficient resource circulation and the high quality services, this paper defined two types of information of products: nominal information and entity information. To support the design of such product life cycle, this paper proposed a method for modeling the product life cycle by simulating the entity information at its design stage. We defined a model of the entity information called Entity Information Model. To create this model, this method derived the entity information by using LCS technique with n-LC Model, which represents the nominal information of the product life cycle. The case study showed that Entity Information Model supports designers for finding out problems in the product life cycles in
terms of the states and quantity of entities to realize the efficient resource circulation and high quality services. In addition, relating n-LC Model and Entity Information Model supported designers for finding out which differentiating factor causes the problem and for evaluating their design that will be caused by resolving the problem from the identified cause.

Future works include the following tasks:

- Developing a framework to collect and manage the information of real-life products through their life cycles
- Establishing a design methodology for product life cycles with service activities

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