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SIMULATION BASED ON PETRI NETS FOR PLANNING LIFE CYCLES AND SUPPLY CHAINS

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ABSTRACT

This paper describes a simulation-based approach to planning products' life cycles and supply chains involving product recovery and disassembly. This approach uses colored petri nets to model the streams of objects(i.e., products, subassemblies, parts, raw materials, regenerated materials, wastes and so on) and their control throughout life cycles. A model is composed of modules, each of which corresponds to a company dealing with a process in a life cycle. The simulation using the model reveals if the objects stream without being stockpiled and how the life cycle impacts the environment in terms of resource depletion and solid wastes. Through the simulations for several life cycles, the best life cycle and supply chain can be determined. The simulation for a copier drum is presented as a validation example.

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INTRODUCTION

Existing and impending legislation has urged many manufacturers to recycle their products. Under the legislation, manufacturers introduced DfD (Design for Disassembly) and DfR (Design for Recycling) approaches to the development of their products(Boothroyd et al., 1992; Nakamura, 1996). This has brought about easy-recyclable products. Nevertheless, not all of such products have been recycled. To promote recycling further, the manufacturers need to plan products' life cycles and supply chains involving product recovery and disassembly. However there is little work on planning them.

To the best of our knowledge, only two works have been done for the planning. Uzsoy(1997) proposed a supply chain model. Though this model is to determine the best mix of new and reused products and subassemblies, the model may be used to determine the best supply chain given a specific scenario. This model is based on a mathematical model, however life cycles are sometimes too complex to make and solve the mathematical model. Nonomura et al.(1999) proposed a simulation-based approach. This approach not only plans life cycles but also optimizes the configuration of products by combining a genetic algorithm with the simulation.

In this paper, we propose a simulation-based approach using colored petri nets(Hisao, 1992). The features of our work are as follows:

- We deal with entire life cycles of products, which include resource mining, material production, distribution, product recovery and so on. This enables the approach to connect with LCA in future.
- The entire life cycles usually include various recycling loops of objects(i.e., products, subassemblies, parts, materials, and so on). The recycling loop of used products is well-known, but there are a lot of other loops: for example, the recycling or reusing of faulty parts or subassemblies yielded at manufacturing stages. We consider such various recycling loops.
- We take account of the fluctuation of the quantities of objects, which occurs according to the fluctuation of the products' demands.
- We model not only the streams of objects throughout life cycles but also their control such as inventory control. The simulation using a model reveals if the objects stream without being stockpiled and how the life cycle impacts the environment in terms of resource depletion and solid waste.
- In our approach, a model is composed of modules, each of which corresponds to a company dealing with a process in a life cycle. Models can be made easily by combining modules, and we can view them easily and

visually. This feature is brought by using the colored petri nets.

- Through the simulation using each of several models in which companies and/or processes are different, the best life cycle(i.e., a combination of processes) and supply chain(i.e., a combination of companies) can be determined.
- The outputs of some CAPP systems can be utilized as the data on modules.

In the following sections, we describe our approach, and then we present the simulation for a copier drum as a validation example.

LIFE-CYCLE MODELS

Representation of Life Cycles Using Colored Petri Nets

We use colored petri nets for modeling life cycles. Figure 1 shows an example of the petri-net representation. “Object Stream model (OS model)” and “Stream Control model (SC model)” represent the streams of objects and the control of the streams respectively. These models are combined, and we call the combined one the “life-cycle model”. This model consists of the following components.

- Places: Each place in OS model expresses the state of an object, and each place in SC model expresses the type of data. For example, the place, “warehouse”, in Fig. 1 represents the state that a part is in the warehouse, and the place, “inventory data”, indicates that the data are for the inventory of the warehouse.
- Tokens: Each token in OS model expresses an object, and each token in SC model expresses data. If the object is countable, one token corresponds to one object. Otherwise (i.e., the object is uncountable), the place can take only one token that represents the total amount of object and its quantity is described in the token as its attribute. If the token expresses the data, the place can also take only one token and the data are described in it as its attributes.
- Transitions: Each transition in OS model expresses the state transition of objects, and each transition in SC model expresses the transaction of data. Occurrence of the state transition or performing the transaction is called “firing of the transition”. The condition and time period for firing are described in each transition. If the condition is satisfied, the transition is fired for the period.
- Arcs: Input arcs pointing from some places to a transition express that the objects or data in the places are required for firing the transition. Output arcs pointing from a transition to some places express that the objects or data in the places are generated or changed as the result of firing.

Firing of Transitions

We can perform simulation using a life-cycle model by firing transitions in succession. At each time in the simulation, it is checked whether the condition described in each transition is satisfied by using the attributes of the tokens in the places that are connected with the transition by the input arcs. If the condition is satisfied, the tokens are removed and the transition is fired for the period. When firing is finished, the new tokens are generated in the places that are connected with the transition by the output arcs. The way to determine the attributes of the new tokens is also described in the transition.

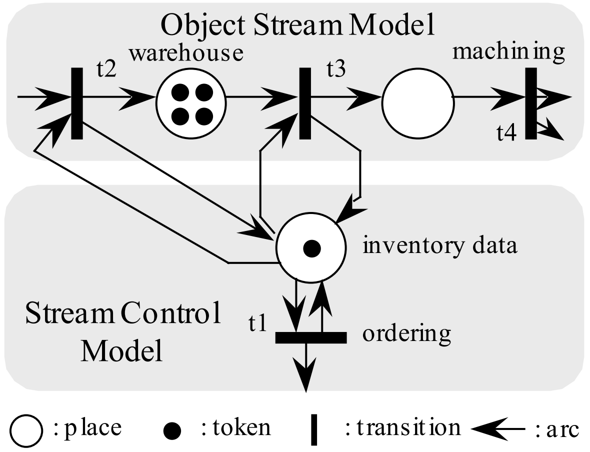

Fig. 1 A part of the life-cycle model.

In the example shown in Fig. 1, the token for “inventory data” has two attributes: the number of parts in the warehouse, *a*; and the number of the parts that were ordered the last time and have been received by that time, *b*. The transition *t1*, which represents ordering a certain quantity of the parts, checks these attributes to determine if its condition is satisfied. The condition described in transition *t1* is whether *a* is less than a lower limit and all the parts ordered the last time have been received by that time. If this condition is satisfied, *t1* is fired and the token in “inventory data” is removed. Then the new token whose attribute *a* is not changed but whose attribute *b* becomes 0 is generated in “inventory data”. The attributes *a* and *b* are also modified when the transitions *t2* and *t3* are fired, which represent the delivery to and from the warehouse respectively.

Attributes of Materials, Parts and Products

The tokens representing materials, parts and products have several attributes which play important roles during the simulation.

Each token representing a material has some attributes such as purity and strength, which are used for choosing end-of-life options. Which types of attributes we need to give to the token depends on the type of the material and/or its usage purpose. We take account of the deterioration of such attributes during product usage, by using numerical formulas. We also consider the deterioration occurring at recycling stages. In this deterioration, a certain value is subtracted from the value of an attribute every time the material is recycled. The values of attributes are also modified when virgin and regenerated materials are mixed.

Each token representing a part has the attribute of the time to failure as well as the attributes of materials used in the part. We give the time to failure by generating exponential or weibull random numbers when we generate the token representing a new part. The exponential or weibull distribution for generating the random numbers differs from one type of part to another. If the part has been disposed but will be reused, the token of the part has also the attribute of the period that the part has been used for.

Each token representing a product has three attributes: the time to failure; list of the parts composing it; and the time when the product usage started. We can calculate the time to failure using the data on the times to failure of the parts. We consider parallel, series, and m/n (m out of n) types of products to calculate the time to failure of the products.

These attributes are used mainly in the simulation of usage and end-of-life stages. However how and which attributes are used depends on the types of products, parts, and materials. In some cases, the time to failure may be used for the judgement whether a disposed product can be reused as well as the judgement whether a product fails at the usage stage. In some cases, instead of the time to failure, the attributes of materials may be used for the judgement whether a disposed product can be reused. The attributes of materials may be also used to choose the other end-of life options(i.e., material recycling, energy recovery, and disposal to landfill).

Generation of Orders

In the simulation, products are ordered by firing a so-called source that is a transition having no input arcs. Time between firing depends on an exponential distribution, and its probability density function is:

$$f(t) = -or \cdot \exp(-or \cdot t) \quad (1)$$

where or is an order rate defined as the order number for a certain period (e.g., a month)(Sadamiti, 1989). We give the order rate of each period before the simulation, and determine the time between firing by generating exponential random numbers in the simulation.

SOFTWARE TOOL

We developed a software tool that enables us to model and simulate the streams of objects easily. To facilitate the modeling of complex life cycles, this tool adopts the following ways:

- The tool includes a module library in which each module corresponds to a company dealing with a specific process. When we make a life-cycle model, we select modules from the module library, and connect them each other. We can also modify a selected module interactively with the tool. When we connect some modules, the tool infers the pairs of places that can be connected each other, and we select some out of them. By carrying out the simulations using some different life-cycle models(i.e., different combinations of modules), we can determine the best combination of companies.
- We developed some CAPP systems for machining, assembly, and disassembly(Takamatsu, 1998; Murayama, 1997a, 1997b). Our tool utilizes the outputs of these systems for modeling. This tool converts the outputs into petri net forms automatically. However, the converted ones are OS models, therefore we need to add SC models to them.

MODELING AND SIMULATION FOR A COPIER DRUM

By using the tool, we carried out the modeling and simulation for a copier drum which is made of aluminum, selenium, and ABS. We deal with the following combinations of end-of-life options for the drum:

Case 1: all the used drums are discarded to landfill.
Case 2: the used drums are material-recycled for the same usage, or discarded to landfill.
Case 3: the used drums are material-recycled for different usage, or discarded to landfill.
Case 4: the used drums are material-recycled for the same or different usage, or discarded to landfill.
Case 5: the used drums are reused, material-recycled for the same or different usage, or discarded to landfill.

The different combinations of end-of-life options mean the different combinations of modules. We also consider the following companies that use the regenerated ABS for the different purposes:

Company *A*: the regenerated ABS is used for producing manhole covers.
Company *B*: the regenerated ABS is used for producing asphalt.
Company *C*: the regenerated ABS is used for producing radio-cassette recorders and toys.

We built some life-cycle models considering these cases and companies on the following assumptions:

- In material recycling, we mix the regenerated material with the virgin one in a certain ratio to produce the material used in new parts. Each type of material has its own ratio.
- The wastes discharged in production stages, such as chips of materials, are recycled in every case.
- The products are used until they fail.

Figure 2 shows the life-cycle model for Case 5. However each process in the life cycle is represented as a rectangle in Fig. 2 because the complete petri-net representation of the life cycle is too complicated to be drawn. Figure 3 shows an example of the petri-net representation of a process. Figures 4, 5, 6, 7 and 8

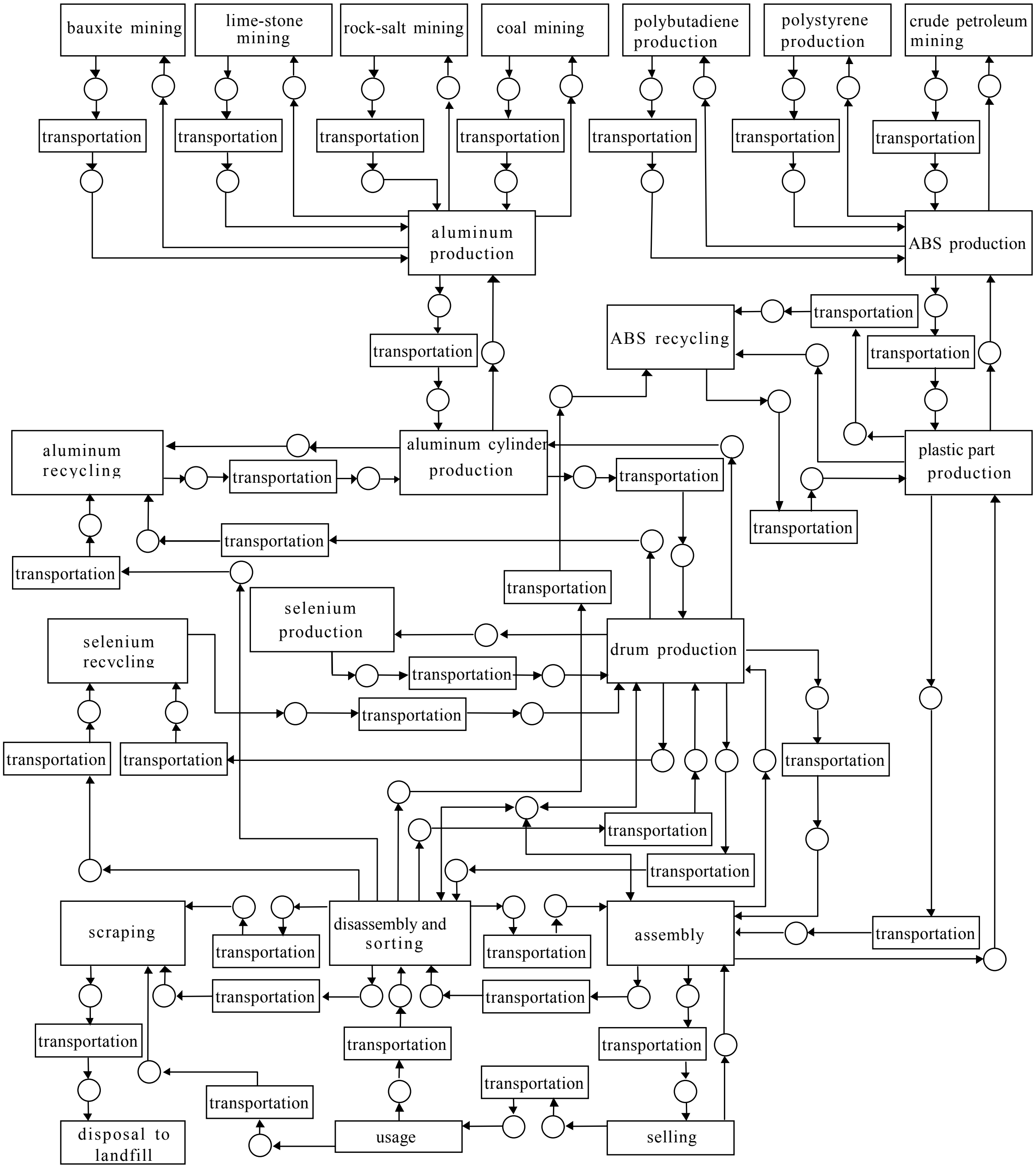

Fig. 2 Life-cycle model of the copier drum.

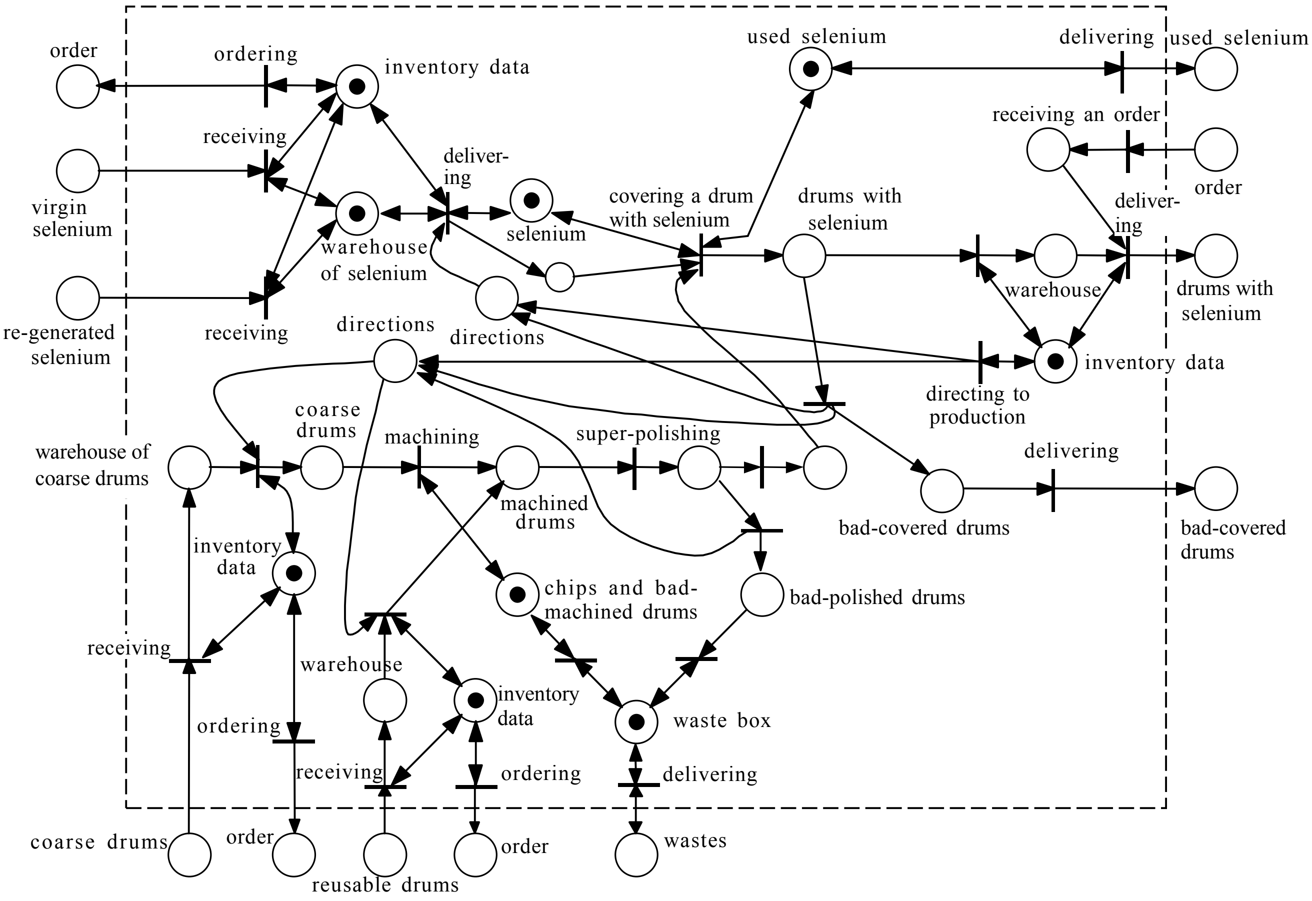

Fig. 3 Petri-net representation of the production process of drums.

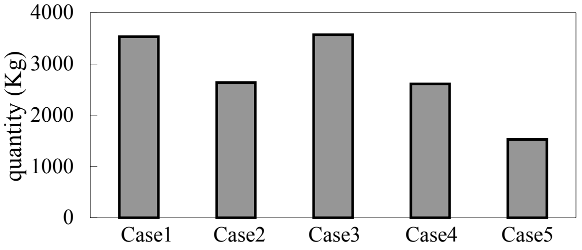

Fig. 4 Resource used for producing the ABS parts of the copier drums.

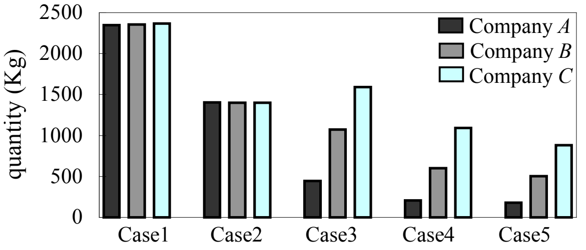

Fig. 6 Waste of ABS used for the copier drums.

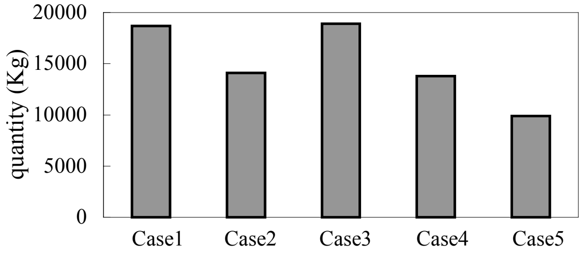

Fig. 5 Resource used for producing the aluminum parts of the copier drums.

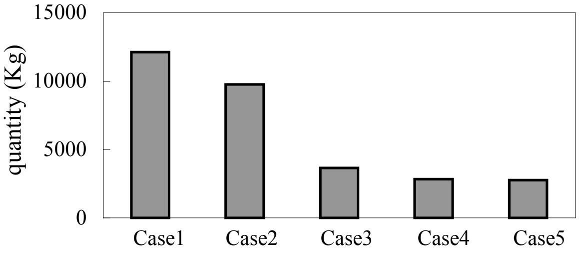

Fig. 7 Waste of aluminum used for the copier drums.

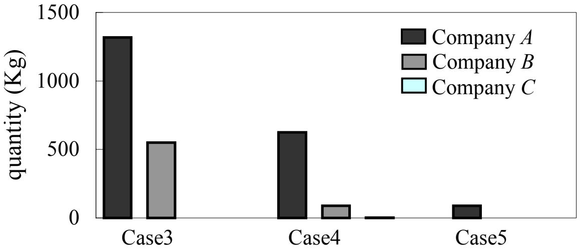

Fig. 8 Stock of used ABS that the recycler has.

show the results of the simulation using the models in terms of resource usage, wastes, and stockpiles. These figures show that the combinations of end-of-life options(especially Case 5) are effective in the reduction of resource usage, wastes, and stockpiles. Figure 6 also shows that the quantity of the wastes in the case of choosing Company *A* is smaller than those in the cases of choosing the other companies. This was caused by the long life span of the products produced by Company *A*. However the regenerated ABS is a little stockpiled in Company *A* even in Case 5 as shown in Fig. 8 because the demand of products in Company *A* is small.

CONCLUSION

We proposed a method of modeling and simulating products' life cycles, and we carried out the modeling and simulation for a copier drum. Future work will connect our approach with the LCA tool we developed before(Namito, 1998) to evaluate some other environmental loads throughout life cycles. We will also extend our method to carry out the cost-benefit analyses of life cycles.

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