PRODUCT LIFE CYCLE SIMULATION WITH QUALITY MODEL

Tomoyuki Hata, Satoru Kato, Hirokazu Sakamoto, Fumihiko Kimura and Hiromasa Suzuki
Kimura, Mohri & Suzuki Laboratory
Department of Precision Machinery Engineering
The University of Tokyo
Hongo 7-3-1, Bunkyo-ku, Tokyo, 113-8656, JAPAN

Abstract: Product life cycle simulation considering the transition of product quality with respect to time is introduced. Parameters representing performance of a product are modeled for expressing quality and degradation and recovery of the performance are calculated. As an example of the simulation, an air conditioner is modeled and its life cycle is simulated. In addition to an ordinary product life cycle scenario, a long life scenario and a lease scenario are examined. Possibilities and limitations of life cycle simulation with quality model are discussed.
Keywords: Life Cycle Simulation, Module, Product Quality

1 INTRODUCTION

1.1 Background

Global sustainability is one of major keywords for the next century. Inverse Manufacturing [1] is proposed for achieving sustainable development. Inverse Manufacturing promotes the circulation of materials and products, and expects that energy consumption should be reduced through material recycling and product reuse. Inverse Manufacturing requires a proper management of product quality, which is one of the most important concepts of Inverse Manufacturing, for establishing a closed loop life cycle. Though it is difficult to have a proper quality management system, we can expect that products be always in good condition with a proper quality control and consequently environmental impacts related to product use be reduced.

1.2 Problems in Life Cycle Management

One of the major objectives of life cycle management is to bring enough benefit to manufactures and, at the same time, to provide satisfactory services for users without causing any serious environmental problems. It is considered that such kind of life cycle management should be built up by establishing a system in which both manufactures and users actively participate. However, it is not an easy task.

There are many difficulties in managing the product circulation efficiently, which is still a small part of the whole targeted system. The problems in realizing a product circulation system are well defined in the area of reverse logistics. According to a review of the studies related to reverse logistics by Fleischmann et al. [2], uncertainties involved in reverse logistics cause the major problems. For example, it is difficult to estimate the amount of the products taken-back and the timing of retraction. Furthermore, it is difficult to estimate the condition of the products taken-back. Production planning and management of maintenance facilities also become difficult due to those uncertainties.

For managing product life cycle efficiently, it is also important to estimate the technological growth and the increase of customer demands. If those factors are ignored, it is not possible to have a proper management system. An ideal system should include both management of the product supply and management of the services. Customers' expectation for the services provided by products could increase due to the latest technologies.

Customers usually use products in different ways in which designers expect. It is difficult to predict how customers use products, and it can bring another problem of product life cycle management. They often keep using old and inefficient products even if they work, which might cause the environmental burden. Continuous use of inefficient products can prevent a proper management of their life cycle.

1.3 Product Life Cycle Design with Life Cycle Simulation

Product life cycle design requires a complete understanding of the targeting product. In addition to product functionality and quality, designers have to pay attentions to environmental impacts, life cycle costing, legislative issues and so on.

Ideally, product life cycle design and product design should be adapted to usage modes of users. An experimental design procedure for constructing a proper product life cycle management system is proposed [3] with considering major constraints discussed above. The procedure for product life cycle design is split into 4 major steps; (1) conceptual design of product life cycle, (2) selection of life cycle scenarios, (3) product design which is adapted to life cycle scenario and (4) development of the management system of the processes included in the designed product system. Life cycle scenario roughly describes the sequences of processes included in life cycle. Life cycle simulation supports the selection of an appropriate life cycle scenario, which can strongly affect the efficiency of life cycle management. Life cycle design based on simulation is expected to help finding some clear clues to overcome the unwilling aspects of the life cycle.

There are various reasons why life cycle simulation might be promising for life cycle design. Some of them are as follows.

- *Specification of Characteristics of a Scenario*
  Life cycle can contain many uncertainties such as recycling rate and technological development, and there have been no definitive methods to estimate them. All the considerable possibilities should be examined by repetitive trials in order to specify characteristics of each scenario. Based on the identification of those characteristics, life cycle scenario should be discussed. Simulation can be a tool for trials.
- *Specification of Target for Design Improvement*
  In addition to specification of the characteristics, it might be possible to find the target of design improvement of product to realize innovative product systems. A sensitivity analysis of the results of simulation will help to estimate the effects of design improvements, for example, an addition of modularity. The difference from the modification of the scenario could be evaluated quantitatively.
- *Improvement of Life Cycle Standards*
  Current life cycles of products are constrained by technological limitations of products and social systems today. If we stick to them, it is difficult to develop desirable product systems. Life cycle simulation can be executed under different assumptions of products and life cycles, and evaluations of them might improve life cycle standards that designers should pursue.

1.4 Scope

When we consider life cycle of continuously developing products, quality plays an important role. Consumers buy new products not only due to physical life of the previously used one, but also due to their functional life, in other words, quality of the product. If we focus on only services provided via products, the current product life cycle systems based on the complete possession might change. For example, sharing cars instead of individual possessions and leases of computers are often discussed, though we have not had a clear answer about which is the best solution from a viewpoint of life cycle management.

The objectives of this study are (1) to improve life cycle models and procedures for life cycle simulation, (2) to examine the differences among several scenarios quantitatively using data under some constraints, (3) to examine the effects of modification of limitations and assumptions for products and technologies and (4) to develop a methodology to design product life cycle and product systems.

In this study, product quality is modeled more precisely than our previous study [4], in that performance indices are derived from the functional relations between modules. Then life cycle simulation with modeling product quality is executed with reliable data obtained from a commercial manufacturer. Finally, appropriate product systems are investigated.

2 LIFE CYCLE SIMULATION

2.1 Related Studies

There are many studies on product life cycle using life cycle simulation for evaluating the life cycle in the research area of mechanical design and manufacturing. Usually reliability draws the major interest of researchers and manufacturers.

From a viewpoint of design, Nonomura et al. simulate several life cycles of fax with assuming different modes of usage, and derive product modularity suitable for each scenario with genetic algorithm [5]. Bras et al. use life cycle simulation for setting design objectives, such as possible recycle rate, in iterative and periodic design renovations [6].

Another direction is to simulate process sequences including recycled materials as well as virgin material. Murayama et al. use Petri-net models for simulation and investigate effective circulation of recycled material [7].

2.2 Product Model and Life Cycle Model

In this study a product is considered to consist of several modules. When one of the modules is out of order, the product loses its functionality and is recovered by replacing the broken module with new one. A product is upgraded by replacing an old module with upgraded one. Product quality deteriorates due to use and is recovered to some extent by maintenance services.

Product life cycle is modeled as a sequence of processes. Processes are; manufacturing, use, inspection, take-back, repair, overhaul, adjustment, recycling, processing for reuse, disposal and so on. Products and material are transferred form one processes to other processes. Each process has its own parameters such as energy consumption, processing costs and waste discharge.

The sequence of the processes depends on the life cycle scenario assigned to the product and its quality management system. For example, long-term use of the product with the complete maintenance is indicated, the life cycle model cares neither the upgrade process nor the recycling process. If a scenario requires the take-back of the products for quality management, the sequence includes processes needed for building it.

2.3 Life Cycle Simulation

Life cycle simulation executes processes following the indication described as life cycle scenario at every small time step. At each time step, new products are manufactured if there are demands. Recycled materials and secondhand modules are used in production as long as it is possible. Products and modules transferred along the sequence defined by life cycle scenario. Figure 1 shows the core part of the flow of life cycle simulation.

Failures and malfunctions of components are generated according to the assigned failure distribution. Physical life of a component is related to failure rate. A product loses its function if one of the modules that are

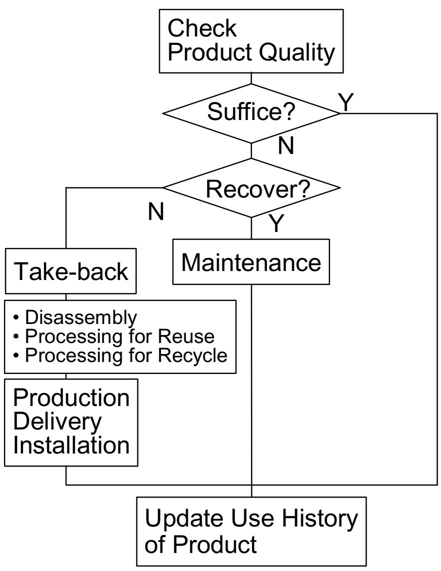

Figure 1: Process Flow after Quality Evaluation

required to perform the function is out of order. When failure of a product occurs, the product is repaired by replacement of broken components or the product is replaced with a whole new one according to the scenario.

Some processes definitely related to the quality of the product, such as inspection, cleaning and overhaul, are executed according to the assigned life cycle scenario. The number of users, which equals the number of products, is fixed through the simulation.

3 MODELING PRODUCT QUALITY

3.1 Quality

In Quality Function Deployment (QFD), function is related to parameters that represent performance of a product. Then function of the product is measured and evaluated quantitatively. The important and difficult point to perform QFD is the mapping from function to such parameters that engineers can handle. The specification of parameters usually cannot be possible until the mechanism with which desired function is performed is decided. Though the mapping is a big problem, quality of a product is related to functional behavior, and can be evaluated by analyzing the behavior [8].

3.2 Quality: Performance and Reliability

In general, quality has many meanings. Statistical quality control concerns mainly reliability and manufacturing errors. For a proper management of product life cycle, as discussed in this study, manufacturers should extend the meanings of quality and quality control. In this study, quality of a product is defined by the combination of performance and reliability in order to reflect trends of customers' demands. When a new model of a product is on sale, some of them buy new one even if the current one still works and the others continue to use the old one as long as it is reliable. The continuous use of an old system for a long time can cause critical environmental problems due to inefficient energy consumptions. For obtaining ideal product systems, consideration of quality, which includes performance and reliability, is introduced.

3.3 Functional Relation between Modules

If a product could be partitioned into independent functional units, each functional parameter of a product is obtained from a parameter of a single unit. However, a functional parameter that represents product behavior often depends on several different modules and derived form the relation between them. For example, energy consumption of a product might have a linear relation and be obtained as a linear sum of energy consumption of each module in the product. The cooling power of a refrigerator might not be represented in a linear relation. It may depend on the performance of a compressor, the efficiency of radiator, capacity of the fridge and so on with nonlinear relations.

To reflect changes in quality due to degradation of modules in life cycle simulation, functional relations between modules have to be modeled clearly. It is important for not only obtaining product quality but also assuming modular upgrade scenarios with replacement of functionally divided units. To make functional relation models, functional block diagrams are used [9]. Physical components are represented as blocks in the model, and transmissions of energy, substances and signals are represented by allows. Constraints at interfaces between modules also specified in this relation model, and then it is used for replacement of the modules.

4 LIFE CYCLE OF AIR CONDITIONER

As a target product of life cycle simulation, a typical air conditioning system for household use is selected. As shown in Figure 2, it has an indoor unit and an outer one. It is characterized as follows.

- It can be used for 10 years.
- Its cooling capability is 2.8kw.
- Filters for an indoor unit can be easily replaced and hopefully replaced in two or three weeks.

4.1 Models and Scenarios

Product Model of Air Conditioner

Major components of an indoor unit of an air conditioner are; a heat exchanger, fans and a motor, a controller, air filters and casings. An outer unit has; a heat exchanger, a compressor, a propeller fan, a motor for spinning a fan, valves and a controller.

Total configurations of the system are expected to be the same for a few decades. However, performance of components of an air conditioner, such as efficiency of a heat exchanging process and capacity of compressor, are improved following the technological development of each component. Controlling units are often completely improved for better performance when the redesign of a system is performed. Design changes in one component often require replacement of other components. Consequently, few components in current air conditioners have possibility for reuse today.

The capacity of heating is modeled with the work and energy efficiency of compressor and quantity of heat

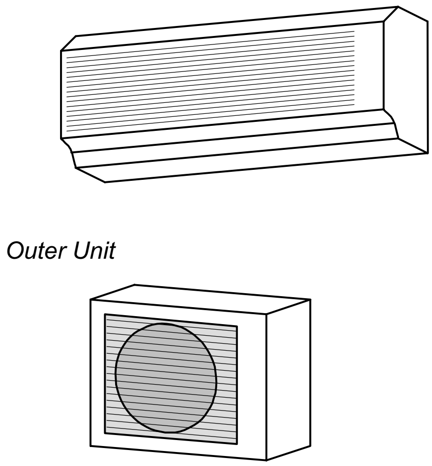

Figure 2: Units of an Air Conditioner

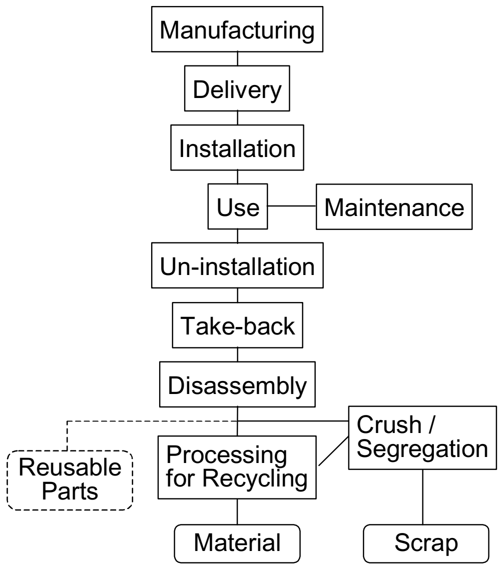

Figure 3: Sequence of processes

exchanged at heat exchanger in an indoor unit. As parameter for indicating quality of an air conditioner, especially performance, heating capacity and averaged energy consumption for a typical usage mode are selected.

Life Cycle Model

The current product life cycle of air conditioners is shown in Figure 3. In the current system, actually no components are reused, so reuse is shown with broken line in this figure. Maintenance contains replacement of air filters of the indoor unit and cleaning of the units.

At their end of life most components are crushed, and materials that can be recycled are segregated from non-valuable scraps. Some components that are made from a single material are separated before crush process with balancing the cost and benefit. Heat exchangers and casings are separated at disassembly process and recycled as material.

The latest performance level of each component is assumed to keep improving gradually. When a product is replaced with a new one, the new one has the latest performance level. Components are degraded while being used. For example, clogging of air filters causes the decline of performance. Those relations for deriving performance from the conditions of components are presented in product model.

Life Cycle Scenarios for Air-conditioner

As a reference of life cycle scenarios, current life cycle is modeled as “ordinary scenario.” In addition to “ordinary scenario,” “long life scenario” and ‘lease scenario” are examined for obtaining a better product systems. The major differences among the scenarios are shown in Table 1. The prices of the air conditioner are set with some differences according to the scenario, but the structure of the air conditioner and the properties of components are the same for all the scenarios.

In “long life scenario,” it is expected that the amount of wastes be reduced. However, performance cannot be good without proper quality control in use phase. Cleaning of the heat exchanger after 7.5 years of use, which is the half of its whole life, is performed as maintenance for such quality control. It is difficult to reuse since they are degraded so much.

In “lease scenario,” air conditioners are periodically replaced. Users have chances to renew products with better performance more frequently than “normal scenario.” It requires costs for delivery and take-back, but users can enjoy better quality. Manufacturers also can have chances to manage product quality, which might increase the possibility for reuse. As long as reliability and technological requirements suffice, components are reused.

4.2 Evaluation of Scenarios

Assuming the same structures, physical life and material properties of current products, three scenarios are simulated for 30 years of use. There are some limitations for recycling plastics under current technologies. If recycling doesn’t pay, crushed components are handled as scrap without recycling.

Amount of Waste

Table 1: Life Cycle Scenarios

Scenario	Life [Years]	Price [JPY]
Ordinary	10	150,000
Long Life	15	150,000
Lease	5	90,000

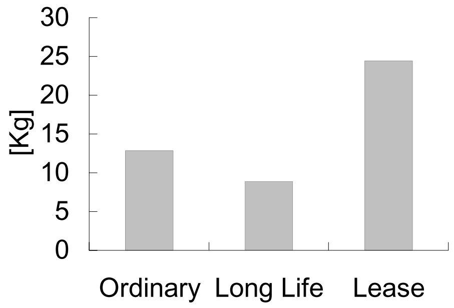

Figure 4: Amount of Waste

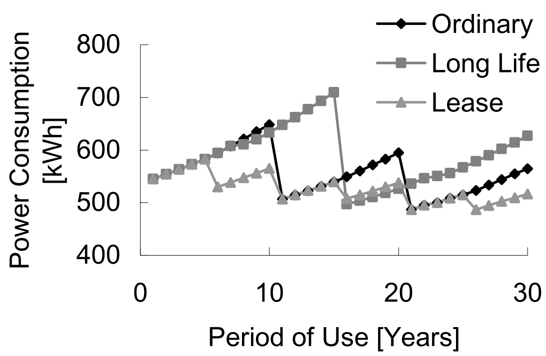

Figure 5: Power Consumption

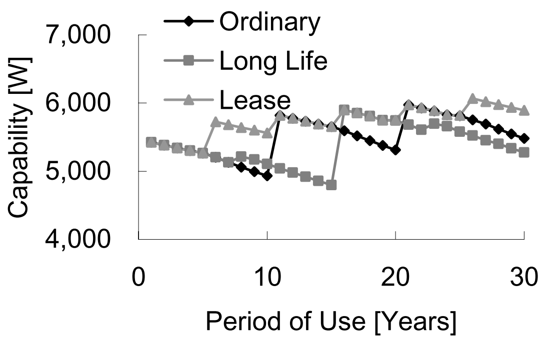

Figure 6: Heating Capability

The amount of waste per user is shown in Figure 4. There are few components for reuse in the current air conditioners. Recycle rate is not set so high because of the cost for recycling and few demands for recycled materials. In lease scenario, most parts of the products are replaced, and a few components are reused. Consequently large amount of waste is generated.

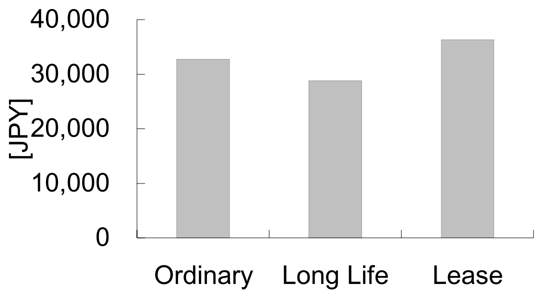

Figure 7: Yearly Cost Paid by Users

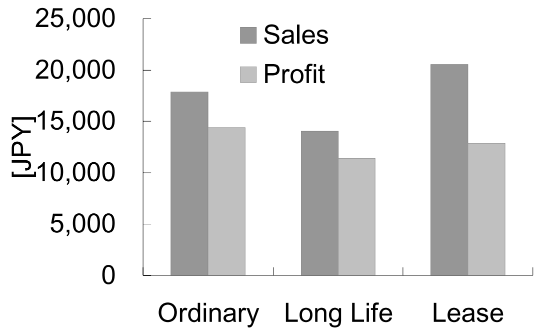

Figure 8: Sales and Profit of Manufacturer (per unit, averaged)

Table 2: Result of Simulation

	LCC (User)	Heating Capability	Amount of Wastes	Energy Consumption in use	Benefit of Manufacturer
Ordinary	1	1	1	1	1
Long Life	1.14	0.98	1.45	0.94	0.79
Lease	0.9	1.04	0.53	1.05	1.15

Quality

As one of the parameters for evaluating quality, the transition of the maximum capacity for heating is shown in Figure 5. Since “lease scenario” can follow the latest technologies due to the circulation in short cycles, air conditioners in that scenario have the best performance. The difference between long life and other two scenarios becomes large after 10 years of use. Even though the air conditioner is properly maintained, the difference becomes large.

The level of performance can have large effects on environmental impacts. Figure 6 shows the transitions of the averaged yearly energy consumption. If lease scenario can save more energy than the energy required for production and circulation, lease scenario may be considered preferable from a holistic viewpoint.

Cost

Figure 7 shows yearly cost paid by users. It shows an average obtained from 30-year-use. Users pay for product, installation, electricity for use, recycling and disposal. Figure 8 shows yearly sales and profit of manufacturers.

Summary

A summary of the simulation result is shown in Table 2. The numerical values are standardized with respect to the ordinal life cycle. The larger the number in Table 2 is, the better. If the long life scenario is applied to an air conditioner with current configuration, where only replacement of air filters and cleaning of a heat exchanger are executed as maintenance, quality doesn’t seem to suffice the demand. Though the amount of wastes is reduced, it forms a trade off against the environmental impact caused by lower efficiency of energy use.

4.3 Improvement of Product Systems of Air Conditioners

Product life cycles are constrained by the limitations of properties of products, such as reusability and recycling cost. In this example of air conditioner assuming current limitations, lease scenario is constrained by the low rate of component reuse and does not have a good result in the amount of waste. If product systems are redesigned considering both product and its life cycle, the results might change completely.

Long Life Scenario with Modified Maintenance

In addition to ordinary maintenance in long life scenario, such as cleaning of a heat exchanger, replacements of functionally important parts are assumed. Motors and a compressor are replaced at maintenance after 7.5 years of use. Figure 9 shows the transitions of yearly averaged power consumption. Due to the modular maintenance, where modules are replaced, performance is improved without increasing the amount of waste so much.

Lease Scenario with Modified Product Properties

If components that are taken-back in short intervals,

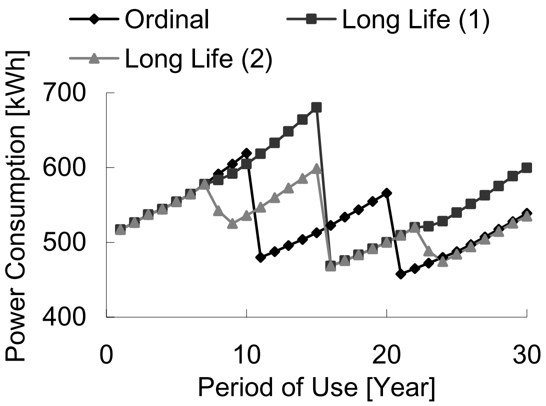

Figure 9: Power Consumption

Table 3: Result of Simulation
(with Modified Product Properties)

	LCC (User)	Heating Capability	Amount of Wastes	Energy Consumption in use	Benefit of Manufacturer
Ordinary	1	1	1	1	1
Long Life 2	1.03	0.99	1.41	1	0.99
Lease 2	0.90	1.04	0.89	1.05	1.15

they might have more chances to reuse after refurbishment. If reuse is increased, the incompetence of the lease scenario that it generates much waste can be improved. It is assumed that motors, valves, a part of frames and control units are reused without preventing technological progresses. The amount of waste is reduced and manufactures' profit is improved. In Table 3 the comparison between ordinary scenario and improved lease scenario is shown.

Summary

Table 3 shows a summary of the results of the modification of scenario. Though modifications are made without complete verification of their possibilities and we cannot show how those modifications can be realized, results of simulation can show the effects of modification.

5 DISCUSSIONS AND CONCLUSIONS

5.1 Discussions on Design Methodology

The differences among life cycle scenarios can be compared quantitatively by executing simulation. Some possible arguments for the simulation are discussed here for pursuing appropriate procedures for life cycle design.

Accuracy of Results of Simulation

Data for simulation, such as price of a component, cost and physical life, are assumed from the current products and processes. The accuracy of the results of simulation strongly depends on those data. There are some inaccurate data such as disassembly cost and disposal cost. Such cost holds at most 5 % of the total costs. The modification of these ambiguous values does not seem to have large effects on the total trends of the scenario as long as the assumption in the proper of range.

Technological growth of each component also has large impacts on the result because that trend is used in quality evaluation. It is not possible to estimate definitive trends of functional growth. We cannot assure the accuracy of this. Also there are many factors that disturb the circulation of products. Some of such noises come from uncertainties included in product systems. For example, only failure of products is included as a factor that disturbs life cycle scenario in this simulation. This simulation lacks models for other factors of uncertainties.

Possibility for Improvement of Product Systems

We started from the same product specification for different life cycle scenarios in this study. Users will choose a product with higher performance when they plan to use the product for a long time even if it costs much initially. In that case, life cycle scenario should be evaluated with the different types of products that fit to those intensions of users.

This study deals the ideal circulation of single product configuration. Replacement of modules is included, but sharing modules in product family is not considered. In general, several types of products are available in the market and modules are shared in the product family. Activating circulation of modules by reuse and sharing is considered as a good approach to realize a closed loop production system. In order to examine such circulation, life cycle model for simulation has to be extended.

As for quality evaluation only a few characteristics are calculated. There could be many other parameters to examine, which are specified with QFD. For supporting quality evaluation with more varieties, functional partitioning and modeling methodologies for modular structure should be extended.

5.2 Conclusions

Quality model is integrated into product life cycle simulation. Though only a few aspects of quality have been introduced, it might be enough for early phases of life cycle design to judge the characteristics among different scenarios. It is not possible to have precise models from the very beginning of life cycle design, and it is rather preferable to omit detailed data and try to catch major trends and characteristics of different product systems. In that sense, life cycle simulation with quality model could help designers identify the characteristics of the scenario they construct. Dynamically changing quality models provide designers with transitions of quality with respect to time, which will help them to planning a better quality management system.

Life cycle simulation is executed more precisely than our previous work with detailed data. It makes possible to perform quantitative comparisons among scenarios or product systems with higher reliability. Quantitative results make it easy to find out the difference among scenario and the effects of design modifications. However, these results do not provide any prioritization of indices, such as amount of waste and heating capacity. Optimization of the scenario has not been considered in this study, and simulation provides only the results of calculation.

The methodology utilizing life cycle simulation in life cycle design procedure has not been investigated fully in this study. Life cycle design in its conceptual phase does not seem to require detailed models of product and life cycle. The levels of abstraction of those models and simulation should be discussed to clarify the methodology for the total life cycle design.

5.3 Future Directions

If manufacturing systems with closed loop is obtained extending current product systems, the only thing designers and engineers have to do is to improve each component and process in traditional ways. However, it seems that product systems should be redesigned form a concept if we aims at a better life cycle from a viewpoint of Inverse Manufacturing. Life cycle simulation should be used for evaluating such different concepts from those of current products. More flexibility for describing life cycle scenario and life cycle model should be implemented for this.

In addition to the improvement of the procedure of describing life cycle scenario and life cycle models, description of usage modes should be incorporated. Then customer can utilize the simulation as a tool for selecting a product that they want by evaluating whether the life cycle scenario provided with the product fits to their demands.

REFERENCES

[1] Fumihiko Kimura and Hiromasa Suzuki, "Product Life Cycle Modelling for Inverse Manufacturing," Life Cycle Modeling for Innovative Products and Processes, (ed. F. -L. Krause & H. Jansen), Chapman & Hall, 80-89, 1995

[2] Moritz Fleischmann, Jacqueline M. Bloemhof-Ruwaard, Rommert Dekker, Erwin van der Laan, Jo A. E. E. van Nunen, and Luk N. Van Wassenhove, "Quantitative models for reverse logistics: a review," European Journal of Operational Research, Vol. 103, No. 1, pp. 1-17, 1997

[3] Fumihiko Kimura, "A Methodology for Design and Management of Product Life Cycle Adapted to Product Usage Modes," Proceedings of the CIRP International Seminar on Manufacturing Systems, 2000

[4] Tomoyuki Hata, Hirokazu Sakamoto, Satoru Kato, Fumihiko Kimura and Hiromasa Suzuki, "Feasibility Study for 'Rapid Product Life Cycle'," Proceedings of the CIRP International Seminar on Life Cycle Engineering, 1998

[5] A. Nonomura, T. Tomiyama and Y. Umeda, "Life Cycle Simulation for Inverse Manufacturing," Proceedings of the CIRP International Seminar on Life Cycle Engineering, 1999

[6] Stewart Coulter and Bert Bras, "Reducing Environmental Impact Through Systematic Product Evolution," International Journal of Environmentally Conscious Design & Manufacturing, Vol. 6, No. 2, 1997

[7] T. Murayama, S. Hatakenaka, M. Namito, and L. H. Shu, "Modeling and Simulation of Products' Life Cycles using Petri Nets," International Journal of the Japan Society for Precision Engineering, Vol. 33, No. 4, pp. 373-375, 1999

[8] Fumihiko Kimura, Tomoyuki Hata and Hiromasa Suzuki, "Product Life Cycle Design based on Deterioration Simulation," Annals of the CIRP, 1998

[9] G. Pahl and W. Beitz, Engineering Design, A Systematic Approach, *2nd Edition*, Springer Verlag, 1996,