博士論文（要約）

Life cycle design of packaging by integrating environmental and functional aspects

（環境性と機能性を統合した容器包装のライフサイクル設計）

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Summary of the doctoral thesis

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Chapter 1: Introduction

Chapter 1 introduces the motivation, general background, objective, and structure of this thesis. An interest in sustainable development has been growing, so that industries need to consider not only their manufacturing line but also the life cycle stages after manufacturing like the end-of-life stage, and consumption stage. That is, life cycle design is required to contribute to sustainable development, where the stakeholders design their target objects or behavior with consideration for the design consequences on the product life cycle.

Packaging is selected as an appropriate case for the practice of life cycle design because packaging plays various roles in society from both environmental and functional perspectives. Packaging is a multi-functional product that connects various stakeholders but inevitably becomes waste. For the integration of environmental and functional aspects of packaging, the life cycles of packaging and its contents should be considered simultaneously. In addition, there are trade-offs between environmental and functional aspects through the life cycle. However, the design consequences of packaging on the life cycles are vague for packaging designers. To understand the design consequences, packaging

design that is currently a function-oriented need to be linked with life cycle thinking.

This study aims to support packaging designers for realizing life cycle design of packaging by integrating environmental and functional aspects. There are four challenges to achieve the aim; (1) to develop a supportive tool to assist packaging designers in understanding their design consequences on product life cycle; (2a) to develop an analytical framework to understand the trade-offs between positive and negative environmental impacts from packaging-derived changes in product life cycle; (2b) to develop an analytical framework to understand the trade-offs between environmental and functional impacts from functionality enhancement; (3) to develop a decision support framework that assists packaging designers in life cycle design. By tackling the four challenges, this study can provide a manner of life cycle design.

Chapter 2: Methods and case studies

Chapter 2 explains the methods used in the thesis and the product cases used for the case study. Life cycle assessment (LCA) was selected as an environmental impact assessment method. The type zero method of integrated definition for function modeling (IDEF0) was selected for activity modeling.

In the case study, the system boundary was defined as the entire product life cycle that indicated the life cycles of packaging and its contents from the manufacturing site to the end-of-life. Packaging designer in the packaging industry was defined as the target stakeholder of this study.

Five consumers' product cases were selected for the case study: packed ham, milk in carton, shredded cabbage, potato salad, and liquid laundry detergent. Because most of packaging was used for food and beverage, four product cases were food products. Also, to expand the applicability of the study, one case was from everyday products.

Chapter 3: Visualization of design consequences of packaging on product life cycle

Chapter 3 provides the results of visualization of design consequences of packaging on the product life cycle through the development of a visually supportive design tool. It is difficult for packaging designers to understand the design consequences on the product life cycle, which is a barrier of life cycle design. To overcome the barrier, attributes allocated to product life cycle were identified as the components of the life cycle. This identification was based on a literature survey and interviews with industrial experts. Based on causal relationships among the attributes, the attributes were connected, where the relationships between attributes were modeled.

To utilize the modeled relationships between attributes in the design stages, two tools: Life Cycle Association Matrix (LCAM) and Function Network Diagram (FND), were developed. Both tools illustrate the relationships between attributes. The way of illustration is a Boolean matrix in the LCAM and arrows in the FND. The LCAM can support alternative generation after identifying the target functions by following the extent of the design consequence on the matrix. The FND can support communication among stakeholders by presenting where the design consequences go in the product life cycle. The two tools enable packaging designers to understand their design consequences on the product life cycle.

The case study was demonstrated to confirm the applicability of the LCAM and the FND in the design procedure. The results of the case study presented that the environmental impacts with consideration for the functional consequences were assessed based on the developed tools.

Chapter 4: Trade-off analysis among environmental impacts of packaging-derived changes in product life cycle

Chapter 4 explains the trade-off analysis among the environmental impacts of packaging-derived changes in the product life cycle. An approach of environmentally conscious packaging design tends

to cause the increase of environmental impacts from the life cycle of packaging and the decrease of those from the product life cycle. However, a framework to analyze the trade-offs in the design stage is yet to be established. This study aimed to analyze the trade-offs between the environmental impacts from packaging-derived changes and food loss and waste (FLW) reduction from consumption stage.

An analytical framework was developed, where there were two analysis methods: trade-off analysis and consumer behavior scenario analysis. The former analysis method provides an indicator to understand the break-even rate of the FLW reduction by compensating for the increase of the environmental impacts from packaging-derived changes in the design stage. The latter analysis method provides a scenario generator that separates consumption stages into six stages. Each stage has two or three patterns that have parameters or models to analyze the FLW in a specific consumer scenario. This analytical framework enables packaging designers to understand the trade-offs among the environmental impacts of packaging-derived changes in the product life cycle.

The case study was demonstrated to show the applicability of the analytical framework and the characteristics of each product case. The results of the trade-off analysis presented that the priority of the functionality enhancement for reducing FLW differed among the product cases. The results of the scenario analysis indicated that there were appropriate combinations of product designs and consumer behaviors.

Chapter 5: Trade-off analysis between environmental and functional impacts from functionality enhancement

Chapter 5 provides analyses of the trade-offs between the environmental and functional impacts from functionality enhancement. An approach of environmentally conscious packaging design is to degrade the functionality for reducing the environmental impacts, where there are trade-offs between environmental and functional impacts. However, an analysis method of the trade-offs is yet to be established. In this study, a questionnaire survey was adopted to quantify the consumers' perceived

values as a functional impact. Two approaches to analyze the results of the questionnaire survey were adopted to quantify the consumers' perceived values. To discuss the trade-offs, eco-efficiency analysis that represents the ratio of the values to the environmental impacts of the target system was conducted.

The approach of the first analysis to quantify the consumers' perceived values was based on the consumers' satisfaction for durable product cases. The case study resulted that the satisfaction-based approach provided the difference of the values of functions and features and the eco-efficiency of designs. However, this approach would be hard to distinguish the product functions that are not remarkable. Thus, the satisfaction-based approach that was based on the consumers' satisfaction was not appropriate for packaging.

The approach of the second analysis was based on the consumers' sufficiency. The case study was selected from food products that have a small portion size. As a result, the approach of sufficiency-based analysis provided the difference in values of packaging functions and the eco-efficiency of designs.

In both analyses, the trade-offs between environmental and functional aspects were quantified. The functional impact assessment can present whether the functionality enhancement from a designers' point of view is to augment the values from a consumers' point of view. The eco-efficiency analysis resulted in the design that decreases the environmental impacts while maintaining the consumers' perceived values.

Chapter 6: Development of decision support framework

Chapter 6 provides a decision support framework for life cycle design of packaging by integrating environmental and functional aspects. Previous chapters resulted in tools and analysis methods to support packaging designers; however, packaging designers do not recognize how to use the results. To utilize the results of the LCAM, the FND, and the two trade-off analyses, it is necessary to develop a decision support framework.

Activity modeling was conducted for framework development. This framework was based on the current function-oriented design procedure to make it easy to apply this framework to the packaging design stages. The top activity was defined as “conduct life cycle design of packaging” from the packaging designer’s point of view, which comprised five sub-activities. The LCAM and the FND went to the top activity as its mechanisms to integrate environmental and functional aspects of packaging in the design procedure. The mechanisms enable packaging designers to integrate the environmental and functional aspects in the packaging design procedure, so that the output of the top activity can be changed from conventional designs to eco-efficient designs.

An application of the framework was presented for discussion by using the results of the case study. The comparison between current function-oriented designs and the framework confirmed the roles of life cycle design. This framework presents the trade-offs between the environmental and functional aspects in the product life cycle, which can assist packaging designers in adopting an environmentally conscious packaging design.

Chapter 7: Conclusion

Chapter 7 concludes this thesis. This study mainly tackled four challenges to achieve the support for packaging designers to conduct life cycle design of packaging. From the results, packaging designers can understand the impacts of product functions on both human beings and the global environment. By understanding the design consequences on the product life cycle, packaging designers can interpret true effectiveness of their designs. Thus, the packaging designers can design packaging with consideration of the design consequences on the product life cycle by integrating the environmental and functional aspects.

Life cycle design would be beneficial for any stakeholder who aims to contribute to sustainable development. To achieve a further contribution to sustainable development, there still remain future tasks. In the product life cycle, there are other trade-offs between environmental and functional

aspects. To conduct life cycle design by all stakeholders, an activity modeling for each stakeholder is also required. Among the layers of the design stages, multi-product system, project life cycle, and transition phase are out of the scope. To confirm the applicability to the product types and the generality, approaches that would be beneficial are discussed.

LIFE CYCLE DESIGN OF PACKAGING

BY INTEGRATING ENVIRONMENTAL AND FUNCTIONAL ASPECTS