Computer Aided Product Service Systems Design

Service CAD and its Integration with Life Cycle Simulation

Hitoshi Komoto

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proefschrift

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Summary

The paradigm of mass production and consumption has dominated the economy of the twentieth century. As a result, a variety of environmental problems such as global warming, resource depletion, water pollution, air pollution, and unmanageable industrial waste, has been caused. At the end of the century, researchers have developed methods and tools for environmentally conscious design (EcoDesign), which deal with these environmental problems from the perspective of product design. However, in order to meet the requirements from our society, further increase of the eco-efficiency of the economy is necessary, with increased added value of products and decreased environmental impacts from a life cycle perspective. Integration of product design into service design, or vice versa, is considered to bring more efficient and effective value addition. Thus, besides EcoDesign tools and methods, methodology to design products and services from a systemic perspective is crucial to meet the requirements. A design methodology based business model to address the challenge is referred to as the Product Service System (PSS) concept. Business models designed based on the PSS concept and the design process are called product service systems (PSSs) and PSS design process, respectively.

Computers are one of our inventions that have changed the economy in the twentieth century. They do not only perform trillions of complicated calculations for us but also help us to carry out our complex intellectual activities. *Design* is considered as one of our complex intellectual activities to create new knowledge about artifacts. Computer software to support the complex activity is called computer aided design (CAD) tools. They have been studied and commercially used in order to increase the productivity of design process and the quality of design solutions for some decades. The increased productivity and quality are derived from the functionality of CAD tools to utilize, store, and share design information. They are further enhanced by computer aided engineering (CAE) tools, which verify and optimize design solutions (mostly) with numeric simulation techniques.

The study described in this thesis is a combination of the knowledge about the PSS concept and that about CAD/CAE tools. Numerous researchers have developed both types of the knowledge. The objective of this study, by combining the knowledge, is the development of CAD/CAE tools used in PSS design process, which is an approach to improve the productivity of PSS design process and the quality of designed PSSs.

Within the scope of this study, first, I propose a systematic method to design service bringing added value to products from a life cycle perspective based on the PSS concept. To support the design process based on the method computationally, I

consider the formal property of design information about products, services, and their interrelated concepts used in the design process. Based on the consideration, third, I develop a prototype CAD/CAE tool to support the design method. Through illustrative usages of the tool for different design tasks (e.g., case studies), finally, I analyze organization and utilization of design information for computer aided product service systems design.

In Chapter 1, background, scope, research questions, delimitations, research procedure and outline, and output of this study are described. Furthermore, the usefulness of this study is described from the perspective of researchers studying methods and tools for PSS design, of designers and entrepreneurs of PSSs dealing with practical design projects, of teachers of PSS design and their students.

In PSS design process, services and life cycles of products are fundamental elements of PSSs. The content of Chapter 2 is review of service modeling methods and life cycle modeling methods in literature. The review is necessary for the development of CAD/CAE tools used in PSS design process. This review clarifies the necessity of a formal method, which represents the design information appearing in existing service modeling methods. The review clarifies appropriateness of life cycle modeling and simulation methods for the quantitative evaluation of the performance of PSSs.

The first part of Chapter 3 is consideration about the formal property of products, services, and their interrelations. The consideration stands on the characteristics of design as intellectual activity, which defines the information about artifacts to meet the given requirements. The consideration leads to a formal representation of the design information used in PSS design process. The second part consists of the architecture and mechanism of a prototype CAD tool for PSS design, which is referred to as Service CAD in this study. Service CAD supports systematic generation of PSS design concepts by utilizing the design information about products and services preliminary stored in it. The final part consists of two illustrative design examples using Service CAD. These examples show the generation process and the preparation process of the design information.

In Chapter 4, integration of Service CAD with a life cycle simulator is discussed. The integration is a solution to complement the limitation of Service CAD in evaluating the quantitative performances of generated PSS design concepts, and in handling the design information containing probabilistic variables such as physical deterioration of products and selection of services by product users. After describing the mechanism and implementation of the life cycle simulator, the integration is discussed. The integrated tool is referred to as ISCL in this study.

After presenting theoretical part of this study, the theory is applied to case studies. These case studies illustrate particular stages in PSS design process, in which quantitative evaluation of PSS design concepts are necessary. Using ISCL in these case studies, types of the design information necessary for the modeling and evaluation of PSS design concepts are analyzed.

Service in a life cycle of products, which is focused in Chapter 5, is crucial for manufacturers to increase the value additions from a life cycle perspective. The types of service considered in this chapter include maintenance and function upgrading services, which are offered in diverse contracts between product users and manufacturers (e.g., ownership delivery, product sharing, and pay-per-function). Furthermore, the behavior of product users with respect to selection of the service and price-based competitions between manufacturers and competitors regarding the service are considered. Methods to model the service, contracts, and user behavior on ISCL are presented together with the analysis and comparison of the service using the simulated results. The analysis clarifies the types of design information critical in designing integration of the service.

A PSS design process for manufacturers includes not only design of the service covered in Chapter 5 but also design of other operations in a product life cycle. In Chapter 6, these operations of original equipment manufacturers (OEMs) are analyzed with ISCL. The simulation model developed on ISCL explicitly defines relations between the operations in their supply chains (e.g., selection of suppliers and order placements to them) and their end-of-life operations (e.g., reuse and remanufacturing). The simulation result is used to evaluate quantitative impacts of these operations on the performance of OEMs from multiple objectives including life cycle costs and environmental impacts. Such a simulation-based analysis integrated with a multi-objective optimization technique is useful in evaluating flexibly of these operations to adapt introduction of new environmental legislations and/or changes of the long-term performance targets of OEMs in terms of these performance objectives.

PSS design in the manufacturing industry can be different form that in the service industry. In Chapter 7, a tourism business model for a sustainable destination based on the PSS concept is analyzed as an example of a PSS developed in the service industry. In the business model, service is designed around the activities of product users (i.e., tourists) and products are flexibly chosen in order to satisfy the needs of tourists. On the contrary, the business models covered in Chapter 5 and 6 is designed around the life cycle of products. This chapter is useful for the comparison of types of design information used in PSS design processes for the manufacturing industry and the service industry.

In Chapter 8, research findings in this study, through the development of a prototype CAD/CAE tool for PSS design and utilization of the tool in different PSS design case studies, are summarized. The types of critical design information to model and evaluate PSSs are identified. The usefulness and limitation of CAD/CAE tools for PSS design are discussed. Changes of the tasks of PSS designers using CAD/CAE tools PSS design are discussed. Furthermore, recommendations for the developers and users of CAD/CAE tools for PSS design, and for manufacturers and entrepreneurs dealing with PSS design in practice are described. At the end of this study, comments by the users of ISCL at PSS design assignments given in one of MSc programs offered by the faculty of industrial design engineering, Delft University of Technology, are presented.

Hitoshi Komoto, 2009

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1 Introduction

In this chapter, background, scope, research questions, delimitations, research method, outline, and output of this study are described.

1.1 Background

The paradigm of mass production and consumption has dominated the economy of the twentieth century. As a result, a variety of environmental problems such as global warming, resource depletion, water pollution, air pollution, and unmanageable industrial waste, has been caused (Tomiyama 1997; Ehrenfeld 2008). At the end of the century, researchers have developed methods and tools following environmentally conscious design (*EcoDesign*) methodology in order to deal with these environmental problems from the perspective of product design. *EcoDesign* methodology has enabled designers and engineers in the manufacturing industry to design products considering the environmental impacts through the entire lifespan. In parallel, researchers in academia have studied product design and life cycle design from an environmental perspective to meet the needs of the manufacturing industry.

The methods and tools developed following *EcoDesign* methodology have supported designers and engineers with a *divide and conquer* style: The life cycle of products was divided into some phases (e.g., production, distribution, utilization, and end-of-life phases), and specific methods and tools were applied to each phase (e.g., design for recyclability, design for reusability). These methods and tools have not been designed to consider interrelations among the individual phases and side-effects due to the interrelations. Thus, they have not been suitable for the design of a life cycle from a systemic perspective.

Service design in the manufacturing industry is considered necessary to further decrease environmental impacts from a life cycle perspective (Tomiyama 2001). Service design is aimed to decrease environmental impacts by structural changes of value additions in product life cycles.

For instance, Fig. 1.1 shows services offered in the life cycle of passenger cars. The structure of value additions is analyzed by observing these services as follows. First, the value of passenger cars is derived from not only its ownership but also its function to deliver mobility. Car rental and car sharing services allow customers to use passenger cars without having ownership of passenger cars. Second, the value of passenger cars is maintained or even increased by repair and upgrading services during the life cycle. Third, providers in the service industry offers other services related with passenger cars. For instance, driving schools and banks offer driving education and financial service (e.g., loan and insurance), which enable car users and car owners to drive and purchase a car. Furthermore, introduction of new providers create new services. For instance, taxi drivers deliver driving effort to passengers. The taxi drivers may have trained their driving skills at driving schools in order to deliver comfort to the passengers.

From an environmental perspective, these services result in additional energy consumption, and they do not directly contribute to the decrease of the current energy consumption. This is why value additions by introducing these services do not simply mean the reduction of environmental impacts from a life cycle perspective. The services have to be *designed* with consideration of additional environmental impacts caused by the services with respect to the value additions.

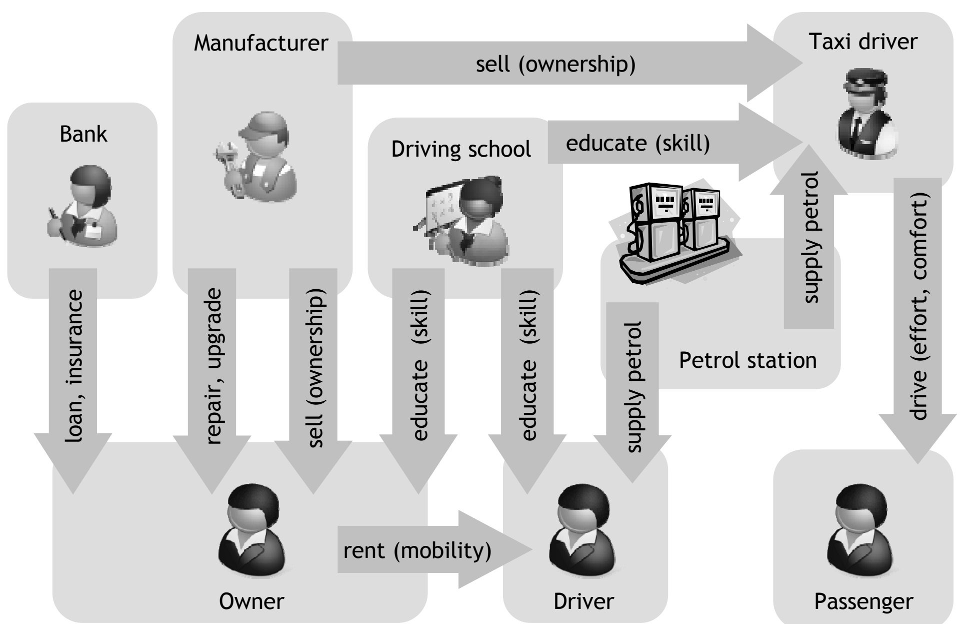

Fig. 1.1 Services with passenger cars and their actors.

Factor X (e.g., Factor 10) is a target measure to indicate measure to indicate the required decrease of environmental impacts under a given time frame (Brundtland 1987). This measure is defined by improved quality of life (as its numerator) with respect to decreased environmental impacts (as its denominator) (WBCSD 2000). According to Brezet and Rocha (2001) incremental functional innovations of products and services are considered incapable of catching up with the required rate of the decrease of environmental impacts. To achieve the required rate, innovations of products and services from a systemic perspective is necessary (Brezet et al. 2001).

To pursue such system-level innovations, the methods and tools based on Eco Design, which are used at the design of individual products, should include services from a life cycle perspective as the focus of the design. As indicated by the numerator of *Factor X*, such a system should be designed in order to add value from a life cycle perspective. This indicates an insufficiency of the design methodology with solely environmental consideration such as Design for Environment (Graedel et al. 1995) and the necessity of design methodology considering economic and socio-cultural perspectives (Charter and Tischner 2001; UNEP 2002).

1.1.1 The Product Service System concept

The Product Service System (PSS) concept has been proposed as a methodology to design innovative business models from economic, environmental, and socio-cultural perspectives. Following the PSS concept, products and services in a business model should be analyzed and designed so that they can jointly satisfy the needs of customers, while realizing sustainable production and consumption (Mont 2002). Business models designed based on the PSS concept are referred to as Product Service Systems (PSSs), and the design process as PSS design process, respectively.

The PSS concept has been explained with different terminologies such as sustainable product systems (Hanssen 1999), alternative function fulfillment (Zwan and Bahmra 2003), and functional sales (Sundin and Bras 2005).

Researchers in the field of industrial design have initially developed the PSS concept. The researchers have studied the concept through several research programs funded by European Union, including Thematic Network of Product Service Development (SusProNet) and Sustainable Consumption Research Exchange (SCORE!). In these projects, the researchers, together with industrial designers and entrepreneurs, have studied design, implementation, and management of PSSs. A special issue in Journal of Cleaner Production (Tukker and Mont 2006) and Tukker and Tischner (2006) include the detail of the conducted studies.

Researchers in the field of production sciences and engineering design have recently studied the PSS concept. The researchers argue that service design in a product life cycle is necessary for the manufacturing industry to create a variety of added value of products in a life cycle, and to prevent price-based competitions that may deteriorate environment of developing countries (Transregio29 2008). For instance, special sessions dedicated for life cycle and service design based on the PSS concept have been organized and planned in recent international workshops and conferences (e.g., life cycle engineering conferences and industrial PSS conferences organized by the International Academy for Production Sciences (CIRP)).

1.1.2 Difficulty in implementing the PSS concept in practice

The PSS concept has not been successfully used in practice in industry, although researchers in academia have conducted substantial amount of study about the concept (Cook et al. 2006). Recent studies have analyzed the causes of difficulty for stakeholders in industry to use the concept for their business model design as follows.

Design theory and methodology - too week theory and too general methodology -

Design theory and methodology for the PSS concept have not been established. From a scientific perspective, design theory and methodology are developed by observing a design process with a set of propositions, whose proof (or refutation) is valuable for designers. For instance, Eger (2007) proposed the theory of product phases by conducting case studies. The theory is aimed at supporting designers to predict the future specifications of products that can evolve during their life cycle. Researchers of the PSS concept have tried to develop theory about the PSS concept. For instance, Tukker and Tischner (2006) proposed three types of business patterns (product-oriented, use-oriented, and result-oriented PSSs) by observing business cases developed based on the concept. Tukker and van den Berg (2006) classified business cases developed based on the concept into eight business types. These cases were evaluated with respect to different value characteristics and summarized in Table 1.1. Irregular variation of the scores and weak comments about the individual score in this figure indicate difficulty in finding general design rules or guidelines about selection of these PSS types with respect to these value characteristics in a specific design case.

Table 1.1 Value characteristics of different types of PSSs after Tukker and van den Berg (2006)

PSS type	User value / market risk		System costs / financial risks		Ability to capture value (now and in the future)			Investment and capability risk	
+ : In general, better than reference 0 : In general, indifferent - : In general, worse than indifferent ! : Critical factor for which a specific analysis is needed Blank: No judgment	Tangible value	Intangible value	Tangible costs	Risk premium finance, transaction costs	power position (% value captured)	Defense to substitutes Client loyalty	High speed of innovation	Investment in PSS development	Other transaction costs
1 Product-related service	0/+	0/+	0	0	0	+	0/+	-/0	0
2 Product-related advice and consultancy	0/+	0/+	0	0	0	+	0/+	-/0	0
3 Product lease	0/+		0/+	0/+	+	+/-	0	-	0
4 Product renting or sharing	!	!	+	-				-	-
5 Product pooling	!	!	+	-				-	-
6 Pay-per-unit use	+		+/0	!	+	+	+	-	0
7 Activity management	+	+	+/0	0/-	+	+	+	-	0
8 Functional result	0	!	+	!			+	!	!

Researchers in the field of engineering design have proposed service design methodology. Tomiyama et al. (2004) proposed a formalization of elements that describe service and explain the purpose of service. Bakiri (2003) and Bullinger et al. (2003) studied service design methodology by introducing taxonomy of service elements. The contribution of these studies has not been clear due to lack of methods to categorize, compare and evaluate the taxonomy proposed in these studies. Sakao and Shimomura (2007) proposed a systematic method for service design. This method situated in a part of product design process. Precisely speaking, this method is used to derive functions and attributes of products from customer's value perception and evaluation. Due to separation of service design from product design, this method cannot explicitly deal with systemic relations between products and services.

Design with multiple objectives for multiple stakeholders – no global optimality –

A business model based on the PSS concept consists of multiple stakeholders (e.g., government, enterprises, and users). The performances of the business model are measured from multiple, economic, environmental and socio-cultural perspectives (UNEP 2002). In the design process of such a business model, appropriate distributions of benefits among stakeholders have to be defined in terms of multiple perspectives. Some case studies reported business models that bring about economic benefits to service providers in both the manufacturing and service industries, while decreasing the total environmental impact (Sundin et al. 2000; Bartolomeo et al. 2002; Maxwell and van der Vorstb 2003; Michelini and Razzoli 2004). These studies concluded that design of such business models required careful adjustment of the balance between economic and environmental performances and conflict resolution among the stakeholders.

In general, Pareto optima are observed in a design task with multiple (conflictive) performance objectives with (conflictive) multiple stakeholders. Pareto optima indicate a set of possible design solutions, which are not inferior to any of the other design solutions from all performance objectives. Pareto optima often indicate existence of the global optimum design solution. The global optimum might be overlooked due to pursuit of optima from single performance objective or by single stakeholder.

Pareto optima should be considered in designing PSSs due to the importance of explicit consideration of multiple performance objectives and multiple stakeholders. For instance, a trade-off between environmental impact and life cycle cost can be considered (Fig. 1.2 (a)). Furthermore, the total profit of stakeholders can be maximized by stopping the pursuit of maximization of the profit of individual stakeholders (Fig. 1.2 (b)). However, the studies quoted in the previous paragraph did not consider alternative Pareto optimal business models or the global optimality of the studied business models.

Difficulty in implementing the PSS concept for manufacturers

Products in business models based on the PSS concept are treated as service channels. Manufacturers, being in charge of design and manufacturing of products, are crucial stakeholders in the business models, while other service providers can be replaced or removed from the business models.

For manufacturers, service had been traditionally treated as a secondary activity, while design and manufacturing of products is the primary activity

(Tomiyama 1997). The traditional thought about services and the fundamental differences between services and products made it difficult for manufacturers to adopt the PSS concept to their own business models.

Nowadays, the role of service for manufacturers has changed dramatically during last decades. Service for manufacturers became crucial to distinguish themselves from competitors, while competitive advantage is hardly obtained through product design. Furthermore, contribution of service (e.g., maintenance, lease, consumer goods supply, and education support) to the corporate profit is not negligible relative to product sales (see corporate reports of, e.g., IBM, HP, and Oce). Nevertheless, services have been difficult to market, price, and sell, as opposed to physical products that have clear indication of function, price, and ownership.

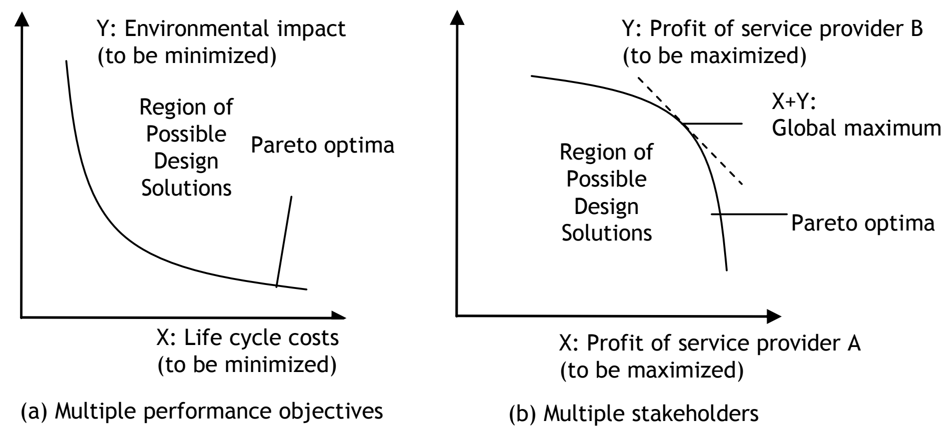

Fig. 1.2 Pareto optimality observed in PSSs in terms of multiple performance objectives (a) and multiple stakeholders (b).

Needs of quantitative and probabilistic evaluation considering uncertainty in a product life cycle at conceptual design

In general, a design process consists of a set of design phases. Of these phases, designers in the conceptual design phase, the overall function of a product is hierarchically decomposed into elemental functions, and appropriate physical principles to meet each elemental function are chosen (Pahl and Beitz 1996).In other words, the overview of structural, behavioral, and functional descriptions of a product is defined at this phase. In the conceptual design phase, the descriptions of products are incomplete (it is still an overview), and they are further refined by defining quantitative information of the products.

Designers have to create the overview of products, while considering various types of uncertainty. For instance, the uncertainty is derived from physical deterioration of products. The deterioration is a stochastic phenomenon, and it might be dependent on how customers use products. Second, the uncertainty is derived from consumer behavior and market situation. Consumer behavior observed at the design phase might be no longer valid when products are introduced into market. Market situation might change due to emergence of competitors, technology advance, or unexpected economic recession.

To cope with such uncertainty at the design phase, designers can model behavior of products and consumers (using probabilistic functions or rules), and simulate the behavior in order to obtain approximate performance of the products (probabilistic design).

Some methods have been applied to the PSS design process. For instance, SWOT (strength, weakness, opportunity and threat) analysis and checklists used in UNEP (2002) support designers to notify potential risks their PSS designs. However, these methods cannot quantitatively assess the risk due to the uncertainty described above. Insufficiency of these methods to deal with the uncertainty implies that the concept of probabilistic design has not been considered in PSS design process in general.

Insufficient knowledge acquisition and knowledge transfer

Cook et al. (2006) studied problems regarding acquisition and transfer of the knowledge to improve the design of business models based on the PSS concept. The knowledge was acquired by the researchers of the PSS concept. The knowledge was then transferred to practitioners in the manufacturing and service industries. The study analyzed the transfer of knowledge in terms of accessibility, mobility and receptivity. In the study, it was concluded that the current transfer was not sufficient for the practitioners to apply the PSS concept for the development of business models. However, the study did not specify the content of missing knowledge to develop business models based on the PSS concept.

The following classification of knowledge shown in Fig. 1.3 can help identify the content of knowledge missing in developing business models based on the PSS concept. Assumed that *P* is the knowledge about products possessed by product manufacturers, and *S* is the knowledge about services possessed service providers. Some knowledge is commonly possessed by them, while other knowledge is not explicitly defined by them. The latter knowledge includes, for instance, knowledge about products and services generated by users. For designers of PSSs, the knowledge about products and services possessed by multiple stakeholders is crucial. For this reason, appropriate infrastructure to transfer the knowledge of different stakeholders to the designers is necessary.

Acquisition and transfer of knowledge has been also focused by the researchers from different viewpoints of product design. For instance, Sandar and Brombacher (2000) showed that reliability of products is improved by explicitly capturing the flow of information regarding the reliability within organizations (in addition to the product description related with reliability).

Tools developed based on the PSS concept -presentation tools rather than systematic engineering design tools -

Design tools in general help improve the quality of design and the productivity of design process. Several tools have been proposed for the generation and evaluation of PSSs (e.g., UNEP 2002). The performance evaluation provided by these tools is subjective to the designers and it is not dependent on the design of business models. This is why the designers cannot identify how to improve the design of business models by observing the evaluated performance. The insufficiency of these tools to support improvement of the design can be explained by the purposes of these tools aimed at by the tool developers. The initiative of the tool development was taken by the designers, who focused on the generation and presentation of conceptual business models (Tukker and Tischner 2006). Tukker and Tischner (2006) also observed that the design of business models in practice is improved by entrepreneurs through its qualitative evaluation and risk analysis during the implementation of business models after the conceptual design.

A service CAD tool was proposed as one of the necessary technologies to improve the productivity of PSS design process by utilization of knowledge about products and services (Tomiyama and Meijer 2003). A service formalization was proposed as the representation to describe the elements of business models by Tomiyama, et al. (2004). However, the computability of the representation has not been verified and concrete functions of a service CAD tool have not been established.

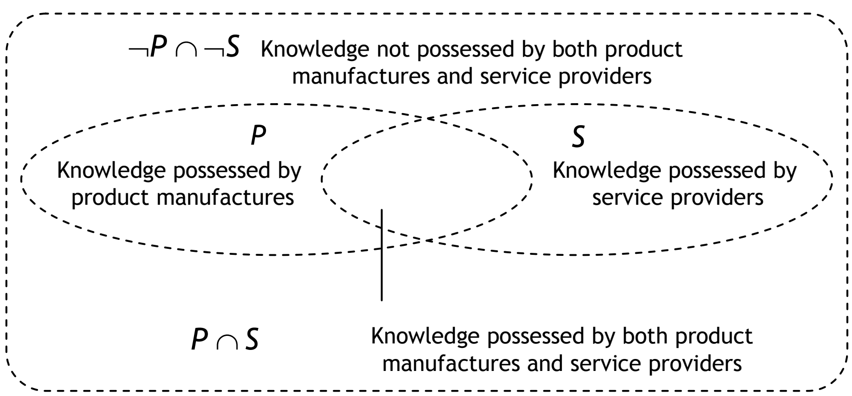

Fig. 1.3 Classification of knowledge about products and services

1.1.3 Computer aided design and engineering (CAD/CAE) tools

Computer aided design (CAD) and computer aided engineering (CAE) tools have been commercially used to increase the productivity of product design process and the quality of products for some decades. Considering the contributions of CAD/CAE tools to product design, computational tools with similar functionalities are expected to support design of business models based on the PSS concept.

The origin of CAD tools is the Sketchpad system developed by Ivan Sutherlands (Sutherlands 1963). The Sketchpad system supported drawing and visualization of design objects (i.e., geometry) using graphic user interface and peripherals (e.g., a light pen). The Sketchpad system has contributed to the discovery of a new method for humans to interact with computers. Functionalities of CAD tools have been advanced to support designers and engineers in describing models, and in sharing and utilizing various types of knowledge in product design process. CAD tools have also contributed to the reduction of time, costs, and errors by automating repetitive design tasks.

CAE tools have been integrated with CAD tools in order to support the verification and optimization of design solutions. In order to calculate the performance of a model defined on CAD tools, CAE tools are typically equipped with large-scale simulation techniques with high numerical precisions such as Finite Element Methods (FEMs).

Functionalities of CAD/CAE tools are not limited to design tasks solely related with geometry (e.g., drafting, drawing and visualization). Hopman (2007) argues that topological (structural) design requires the creativeness of designers in comparison with geometric design. Considering the use of these tools in a wide range of design tasks, these tools are expected to possess the functionalities related with decision makings of designers and engineers as follows (Hatamura 1993).

- Function to give information necessary in the decision making
- Function to express the contents of the decision making
- Function to support the decision making (by informing constraints in a design and notification of the violations)

To support the conceptual design process, a few CAD tools have been proposed (Tomiyama et al. 1993; Welch and Dixon 1994; Umeda et al. 1995; Bracewell and Sharpe 1996; Yoshioka et al. 2004). As an example, interfaces of Knowledge Intensive Engineering Framework (KIEF) system are shown in Fig. 1.4. As shown in the figure, these CAD tools do not use purely geometric and quantitative design information to support designers. Instead, they use qualitative but formal representations of functions, behavior, and structure. The representations enable AI (artificial intelligence) techniques to simulate and interpret qualitative physical behavior (e.g., de Kleer and Brown 1984; Forbus 1984). These techniques enrich the facilities of these CAD tools. For instance, the FBS modeler (Umeda et al. 1995) on the KIEF system supports modeling of relations between function and behavior of a product. The modeler is equipped with a technique to verify the relations based on qualitative behavioral simulation. A CAD/CAE tool to support PSS design process is expected to possess similar kinds of computational supports.

Challenges of CAD/CAE tools to tackle these problems in PSS design

The problems in designing PSSs described in Section 1.1.2 can be interpreted as the challenges for the researchers of CAD/CAE tools to improve PSS design process. In summary, these problems are partly related with the insufficiencies of the existing methods and tools in supporting the following aspects in PSS design process.

- Reflection of research findings about the PSS concept into PSS design.

- Representation of information used in PSS design process.
- Systematic design of PSSs.

Therefore, development of CAD/CAE tools with functions to overcome the above insufficiencies effectively improves PSS design process.

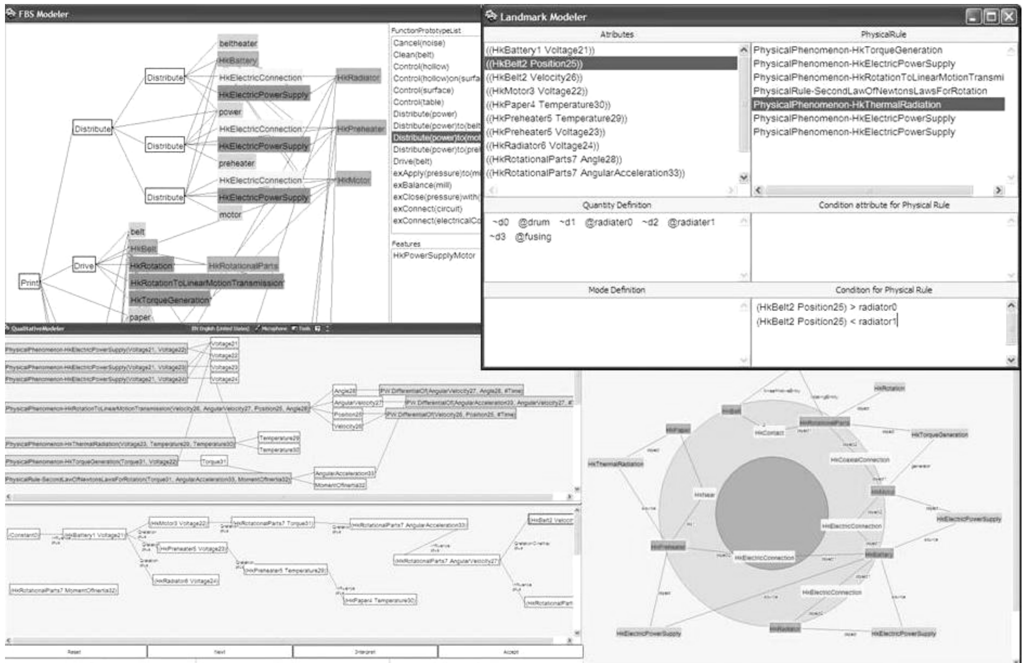

Fig. 1.4 Interfaces of the KIEF system to support conceptual design.

1.2 Research objective

As described in the previous subsection, some design problems found in PSS design processes can be solved by utilizing design information, and by transferring research findings about the PSS concept from academia to industry. Since CAD/CAE tools have contributed to utilize and transfer design information, developing CAD/CAE tools for PSS design is considered helpful to improve PSS design processes.

The main objective of this study is to contribute to the development of such a CAD/CAE tool for the improvement of PSS design processes. However, this objective is too broad to form research questions to be answered. Therefore, in the next subsection, the scope of this study is defined and its objective is refined. Furthermore, delimitations of the study are explicitly described at the final subsection.

1.2.1 Scope and assumptions

An appropriate scale of the scope of this study is specified by introducing the following assumptions.

Assumption 1 (Sustainability by PSS design)

In this study, it is assumed that *product service systems design improves the system performance in terms of sustainability* (Brezet et al. 2001). The purpose of this study is not to defend this assumption. In other words, this study does not justify generic superiority of business models based on the PSS concept to other alternative business models from a sustainability perspective. Instead, the purpose of this study is to show the usefulness of CAD/CAE tools in designing PSSs, which satisfy this assumption.

Furthermore, the aim of this study is not to propose an indicator to measure the sustainability performance of business models, which is used to evaluate this assumption. For readers interested in study about such indicators, please refer to study about eco-efficiency (WBCSD 2000), including, for instance, Volgtlaender (2001) for Eco-Value Ratio (EVR), an integration of a LCA-based cost and a value description.

Assumption 2 (R & D of CAD/CAE tools to improve PSS design processes)

In this study, it is assumed that *research and development of CAD/CAE tools for PSS design can improve PSS design processes*. To proof or falsify this assumption is out of the scope of this study. The reason is that some of the tools have not been commercially used in industry, while they have been researched and developed in academia for more than four years, or a PhD time (e.g., Yoshioka et al. 2004).

There are alternative studies considered to support the improvement of PSS design process. These studies include update of PSS design guidelines (e.g., UNEP 2002), continuation of empirical studies (e.g., Berchicci 2005; Tucker and Tischner 2006). However, this study focuses on the research and development of CAD/CAE tools, as another opportunity to improve PSS design processes. Nevertheless, these alternative methods and tools are referred in this study in order to form the background of this study.

Assumption 3 (Definitions of design information and design activity)

Considering the use of a CAD/CAE tool in a PSS design process, the representation and usage of design information on the tool is crucial. Therefore, the following definition of *design information* and *design activity* are assumed in this study. *Design information* is classified into that of design objects (e.g., structural and behavioral descriptions of products in product design) and that of design specifications (e.g., function requirements in product design). *Design activity* is to define information about the design objects and design specifications, and correspondences between them (Tomiyama 2002). The importance of these definitions in context of this study is that these definitions treat a design process as a systematic activity, in which design solutions are obtained after finitely defining design information, and in which design solutions are verified by observing the correspondences. This perception of a design process is widely accepted in context of engineering design (Pahl and Beitz 1996). Consequently, the definitions require a CAD/CAE tool to support systematic search and verification of design solutions. For readers interested in the role of a formal model to represent design information and design process in the development of a design tool, please refer to Takeda et al. (1990).

Assumption 4 (Necessity of improving transferability of knowledge about the PSS concept)

As introduced in Section 1.1.2, a number of studies have been conducted to clarify the characteristics and types of PSSs with a scientific attitude. However, the purpose of this study is neither to generate new types or patterns of PSSs as hypotheses, nor to proof or falsify the accumulated knowledge about the PSS concept. Instead, this study will investigate how to improve the transferability of the accumulated knowledge about the PSS concept and about products and services for PSS design in practice.

1.2.2 Research questions

The above assumptions specify the scope of this study. Based on the background and these assumptions, the objective of this study is to *improve the PSS design process as designer's systematic information creation activity, which is supported by computational facilities, while reflecting research findings about the PSS concept in the design process*. To achieve this objective, answers to the following questions are fundamental in developing the basis of computer aided PSS design.

Research Question 1: What kind of design information is/will be used in PSS design processes, and how will they influence the design of PSSs?

This research question is related with the following sub research questions.

- **RQ1a**: What is the utility of methods and tools currently offered in academia in dealing with design information in PSS design processes, while considering the research findings about the PSS concept?
- **RQ1b**: Is there any implicit design information useful in PSS design process? What are the effects of the explicit usage of such information at specific tasks (e.g., modeling and evaluation) in PSS design process?

Research Question 2: How can the information identified by answering RQ1 be organized and utilized for computer-aided systematic PSS design?

This research question is related with the following sub research questions regarding the functions of CAD/CAE tools for systematic PSS design.

- **RQ2a:** How can CAD/CAE tools support/delimit organization and utilization of design information for systematic PSS design?

- **RQ2b:** How can the design information organized for systematic PSS design using CAD/CAE tools influence the tasks of PSS designers and the distribution of tasks among members in a PSS design team?

1.2.3 Delimitations

Answering the above research questions in scope of this study does not mean that all problems regarding the representation and utilization of design information in the PSS design process under computer-aided environment are resolved. These are the delimitations of this study.

Delimitation 1: Generalization of research findings

Researchers of the PSS concept have tried to generalize research findings of their empirical studies (see Section 1.1.2). For instance, they have classified business models based on the PSS concept into a set of PSS types (e.g., shared service) by comparing these business models. This thesis includes comparisons of PSS business models, which partly correspond to these PSS types. The comparisons are made by simulating the performance of these PSS business models (Chapter 5, 6). However, the purpose of the comparisons in this study is not the generalization of the research findings obtained by these comparisons (also see Assumption 1 of this study in Section 1.2.1). In this study, the purpose of the comparisons is to analyze the types of design information, which makes such comparisons possible.

Furthermore, these comparisons are made under given parametric conditions. Since the performance of a PSS business model depends on the parameter values in the model, the performance does not characterize the generic performance of the PSS business model. Thus, for the generalization of the research finding obtained from the comparisons, further comparisons under different parameter conditions and model assumptions are necessary.

Delimitation 2: Visualization of PSS design information

Visualization of PSS design information is crucial for designers to understand PSSs. Since the design information does not have geometric property, the visualization is a naturally difficult task. Similar difficulty is observed in the visualization of design information during a conceptual product design stage (see Fig. 1.4).

Before studying the visualization of PSS design information (How PSS design information is visualized?), study about PSS design information is necessary (What is PSS design information?). This study focuses on PSS design information, not its visualization.

Delimitation 3: Selection of case studies

Selection of case studies in a dissertation is crucial to effectively answer the formulated research questions. This study has limitation in selecting case studies following these criteria.

- Case studies should cover the design of PSSs both in the manufacturing industry and in the service industry. This criterion is useful to clarify the differences of PSS design processes between two industries. Furthermore, the criterion is useful to evaluate applicability of the method and tool proposed in this study, to the design of PSSs in both industries.
- Case studies should be related with the past or ongoing research projects conducted by the same parent organization (of the author of this thesis). This criterion means that there is less difficulty in collecting the design information to comprise these case studies.
- Case studies should collect attentions from the researchers studying the PSS concept or relevant subjects. This criterion means that the results of these case studies are academically valuable (i.e., publishable) independently from the context of this study.

In spite of these criteria, the selection procedure is inevitably subjective due to the number of possible PSS business models. Thus, the application part of this study (See Section 1.3) is an explorative study. However, these selection criteria increase quality and homogeneity of the exploration.

Delimitation 4: Discussion about usage of PSS design information

Design information used in a PSS design process can be used at the implementation and management of the PSS, as (product) design information is used during the all stages is a product life cycle. However, this study focuses only on utilization and organization of design information in PSS design processes. Its utilization and organization at the other stages is not discussed in this study.

1.3 Research procedure and its outline

As presented in the previous subsection, the research questions have been presented. In order to answer these research questions, this study adapt a research procedure consisting of four research steps; review, theory, application, and conclusion. The outline of the procedure is described in Figure 1.5. The detail of each step is described as follows.

Review (Chapter 1 and 2)

Before answering the research questions, the state of the research in academia relevant to the research questions has been identified. First, problems in PSS design processes have been identified by reviewing studies about the PSS concept

(Section 1.1.2). The review focused on the problems due to insufficient usage of PSS design information in PSS design processes. After that usefulness of product CAD/CAE tools in organizing and utilizing design information have been presented in order to draw attention to the necessity of the development of similar tools to support PSS design processes (Section 1.1.3). To develop the theoretical foundation of such CAD/CAE tools for PSS design, methods and tools, which systematize the modeling of services and life cycles and the evaluation of the model performances, are reviewed (Chapter 2). The review focuses on the capability of the methods and tools to deal with design information used in PSS design processes and the research findings of the PSS concept. This review is a basis of the answers to the research question RQ1a.

Theory (Chapter 3 and 4)

To answer the remaining research questions (RQ1b, RQ2a, and RQ2b), a prototype CAD/CAE tool to support PSS design processes is developed. For the development of the tool, a formal model of PSSs employed in the tool is necessary.

New models of PSSs can be ad-hoc, or not logically connected with the related research findings. In order to avoid such a model of PSSs, rigorous survey of existing models dealing with similar design problems is necessary. For instance, models of services and life cycles have been developed to deal with similar design problems appearing in PSS design process. Thus, the formal PSS model proposed in this study is based on service modeling methods and life cycle modeling methods reviewed in the previous chapter.

Development of a CAD/CAE tool is valuable as a content of a study to understand a design process. It helps researchers to understand design problems in the design process, and identify the types of design information required for computers to describe and solve the design problems (Welch and Dixon 1994).

A CAD/CAE tool for PSS design is developed at two discrete steps in this study. Each step corresponds to the support function of a tool at a major task in PSS design process. One is to support conceptual design of PSSs, in which PSS design concepts are systematically generated. The other is to support evaluation of PSSs, in which the performances of generated PSS design concepts are calculated using numeric computation. These functions are necessary at an early phase of design process (conceptual design). The tool developed in this study corresponding to the former function is called *Service CAD* (Chapter 3), as one of service modeling tools (Section 2.2). The tool for the latter function is called *ISCL* (Chapter 4). *ISCL,* an integration of *Service CAD* with a life cycle simulator, calculates the performances of a life cycle of products using life cycle simulation (Section 2.1). Since the representation of design information used in *ISCL* is an extension of the formal model of PSSs proposed in Chapter 3, *ISCL* is comparable to CAD/CAE tools for product design, in which designers define product models with a geometric modeler and analyze the performances with computational methods such as finite element methods (FEM).

ISCL (including *Service CAD*) is necessary in answering the remaining research questions RQ1b, RQ2a, and RQ2b. The tool is crucial to identify advantages and disadvantages of computer-aided PSS design. For instance, the degree of freedom in organizing and utilizing design information for PSS design is restricted in computer-aided PSS design, while the restrictions are necessary for more effective (computational) utilization of the design information for systematic PSS design.

Applications (Chapter 5, 6, and 7)

ISCL developed in the former step is used to answer the remaining research questions (RQ1b, RQ2a, and RQ2b) through PSS design case studies. Selection of case studies among possible alternative cases is crucial to effectively identify the advantages and disadvantages systematic PSS design using dedicated CAD/CAE tools. Through the identification of the (dis)advantages, the sub research questions RQ2a and RQ2b will be answered. These case studies are crucial to answer the sub research question RQ1b. To do so, first, the usage of specific design information used in each case study is identified. Second, the effects of such design information on the performance of the designed PSSs are identified. Selection criteria of the case studies and delimitation of this study regarding the selection are described in Section 1.2.3.

ISCL is first applied to PSS design focusing on the service in a product life cycle (Chapter 5). The service includes maintenance and functional upgrading services, while considering diverse stakeholder ownership relations and packaging of individual services. These services are actively studied by the researchers in the field of Industrial Product Service Systems (Transregio29 2008), because the sales of these services are not negligible for manufacturers.

Second, ISCL is applied to PSS design focusing on other operations (than service; e.g., reuse and remanufacturing operations) in a product life cycle (Chapter 6). These operations have not included in the focus of the case study in Chapter 5. However, design of these operations influences the product flows in a life cycle, and the overall economic and environmental performances from the perspective of manufacturer. This case study also deals with the design of these operations from multiple perspectives (e.g., life cycle cost, environmental impacts).

Third, ISCL is applied to PSS design of a business model at a sustainable destination (from the perspective of the service industry). Such business models are different from those in the manufacturing industry studied in Chapter 5 and Chapter 6. Accordingly, the required PSS design information can be different from the design information used in those case studies. In those case studies, a set of services are defined with respect to the given products, and configured around the life cycle of the products. On the contrary, tourism business models are developed based on the needs of tourists during a trip, without explicitly specifying products and facilities used and offered in the trip. Considering such a difference, the economic performance of a tourism business model designed based on the PSS concept is studied.

Conclusions (Chapter 8)

At the final step of this study, the results of study obtained at the former three steps are summarized. The research questions are answered. Furthermore, recommendations regarding the future of systematic PSS design using CAD/CAE tools are drawn. This step is described in Chapter 8.

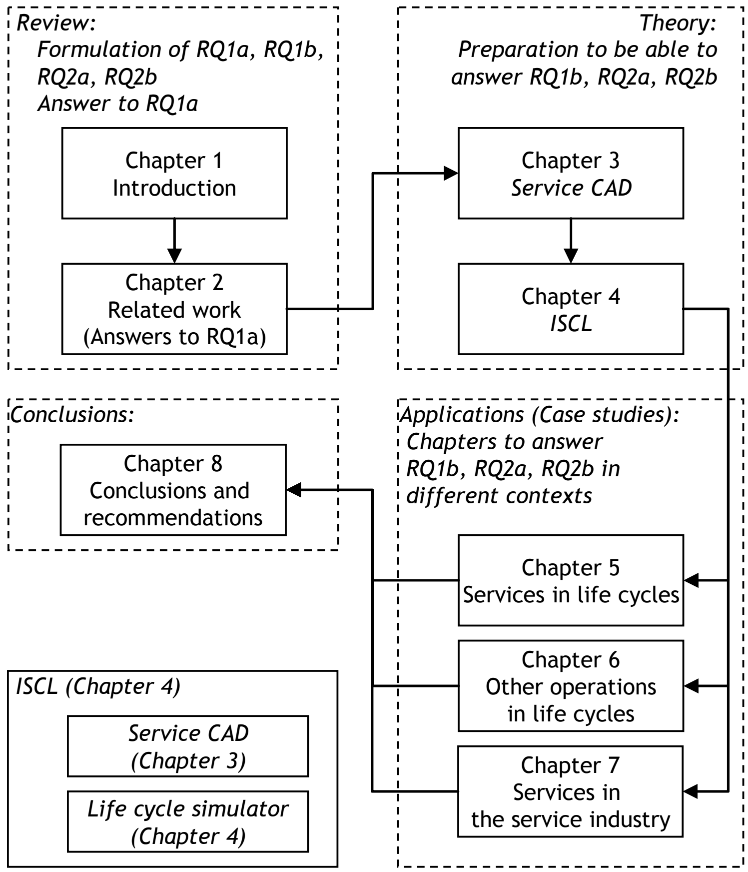

Fig. 1.5 Outline

1.4 Output

The output of this study is the knowledge to utilize design information for systematic modeling and evaluation of PSS design concepts. The research questions have been answered through the development of such knowledge. This study is considered useful for the following types of readers.

- Potential users and developers of methods and tools to support systematic PSS design will learn the states of arts of those methods and tools developed in academia.
- Designers of business plans in industry will also benefit from this study in organizing information about their products and services included in the business plans. Drawing business plans following a modeling method will help the

designers systematically analyze how these products and services satisfy the needs of customers.

- Students learning PSS design and teachers giving lectures about PSS design will also benefit from this study in clarifying the role, knowledge, and skill of PSS designers as system integrators in a computer-aided systematic design environment.

Furthermore, output of this study includes a prototype CAD/CAE tool based on the investigation in Chapter 3 and Chapter 4. The tool is called *ISCL* (Integrated *Service CAD* with Life cycle simulator. The tool has been used to conduct case studies in Chapter 5, Chapter 6, and Chapter 7. The tool has been used by students during the course "product service systems" in a master course program offered by Faculty of Industrial Design, Delft University of Technology. Some comments about the tool in terms of usability and functionality are summarized in Appendix B. The tool has also presented at a guest lecture for a sustainable destination in North Holland (partially described in Chapter 7), at Stenden Hogeschool, Leeuwarden, the Netherland.

2 Related work

In the previous chapter, problems in PSS design process have been identified. Development of computational facilities to utilize and organize design information used in the process has been proposed as a solution to the problems. In this chapter, methods and tools for life cycle modeling and service modeling in literature are reviewed. The purpose of the review is to form the basis of a modeling method employed in service CAD tools for PSS design, assuming that services and life cycles of products as fundamental elements of PSS design concepts. Availability and limitations of the reviewed methods and tools are investigated in order to complement the inefficiency of the current methods and tools used by PSS designers in dealing with PSS design information (Section 1.1). The conclusions of this chapter include the specification of a PSS modeling method for systematic PSS design based on the review.

2.1 Life cycle modeling for life cycle design

First of all, this section starts with the classification of modeling methods and tools to design a product life cycle. After that life cycle simulation (LCS) is introduced as a method to design a product life cycle. The history, the working principle and the applications of LCS, and the tools support LCS are also introduced. Then, the LCS-based method is compared with other modeling methods for design of product life cycles. The comparisons are made with respect to the treatment of multiple design objectives and the calculation of the performances of product life cycles.

2.1.1 Horizontal integration and vertical decomposition methods

The modeling methods to design product life cycles are classified in Fig. 2.1. Some methods focus on an aspect of product design, which particularly corresponds to a single process in a product life cycle (e.g., design for disassembly, design for recyclability). These methods are the members of so called Design for X (DfX) methodology (e.g., Greadel and Allenby 1995). Others focus on the holistic performance of a product life cycle, which is obtained by integrating the performances of individual processes in a product life cycle. LCS, Life cycle assessment (LCA), and life cycle costing (LCC) are examples of these methods (Dujairai et al. 2002). These two types of methods are also called vertical decomposition methods and horizontal integration methods (Shu et al. 1996).

Among the horizontal integration methods, LCS is different from LCC and LCA in that LCS considers dynamic interdependency of the processes within a product life cycle to calculate the performances of a product life cycle, while LCC and LCA calculates the performances by aggregating the performances of the independent processes. For instance, LCS simulates the quantitative impact of increasing intensity of a reuse process (by increasing the collection rate of products, for instance) on the decrease of material extraction and on the increase of inspection of the reused products. LCS is suitable for the design of a product life cycle to understand such complex interdependency among the processes, while LCC and LCA are useful to identify the processes that have major impacts on the performances at a high quantitative precision. (The precision depends on the quality of employed life cycle inventory.) Those horizontal integration methods are described in detail shortly.

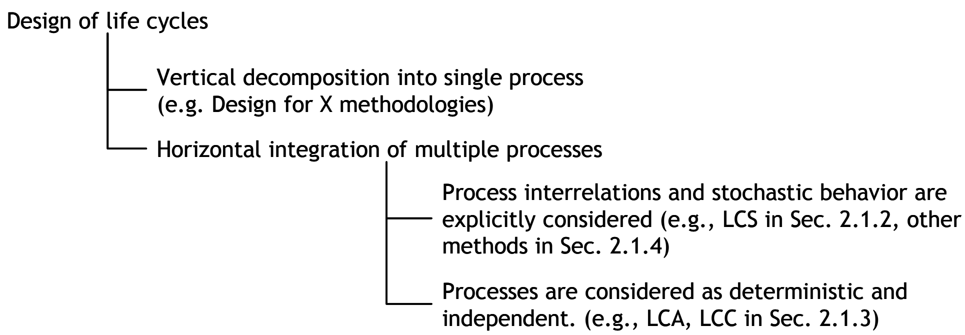

Fig. 2.1 Classification of methods for design of life cycles

2.1.2 Life cycle simulation

History

Pilot work to develop the concept of LCS has been carried out at the University of Tokyo (e.g., Masaoka et al. 1996; Johansen et al. 1997). The concept has been developed to validate sustainable model of products. Around the same time, but independently, Shu et al. (1996) employed a probabilistic reliability model of wear and failure of mechanical fastening elements to design the product life cycle subject to life cycle costs. Hata et al. (1997) simulated deformation of plastics of a film with lens mechanism with a finite element method. The simulation result was used for failure mode and effect analysis (FMEA) of the mechanism. Takata et al. (1998) simulated aging behavior of the components of assembly robots. Using the simulation results, the components were redesigned with respect to the given assembly tasks in a manufacturing facility. The simulated aging behavior was verified with experiments. Umeda et al. (2000) and Fujimoto et al.(2004) evaluated and optimized the modular structure of a refrigerator (Umeda et al. 2000) and fax machines (Fujimoto et al. 2003) using genetic algorithm, respectively. The modular structure was optimized with respect to the environmental impact and the corporate profitability. These studies considered a variety of end-of-life operations. LCS models employed in these studies have been used as reference models for the succeeding LCS-based studies described in the following subsections.

Working principle

Figure 2.2 shows the evaluation framework of the performances of a product life cycle using LCS. Behaviors of a product life cycle are represented by dynamic flows of information, material, and money among the manufacturers, users, and other service providers in a product life cycle.

To generate a behavior of a product life cycle using LCS, product and process models are defined. A product model consists of a set of modules. The modules possess physical and functional states. They also possess parameters that influence the corresponding state transitions (e.g., failure rate and function lifetime). A process model changes states of products based on these parameters. It also generates material, information, and financial flows among processes. Each process model possesses specific economic and environmental costs to determine the amount of respective flows per process activation. Quantitative values used in product models and process modes are referred to as life cycle data, and they are stored in the life cycle data base.

Behavior of individual product and process models determine systemic behavior of a product life cycle, because individual behaviors are interrelated. For instance, the physical deterioration of a product depends on its usage (i.e., how frequently, long, or intensively products are used), while the states of products (e.g., model year, mileage) are major determinants to select an end-of-life option (e.g., recycle, remanufacture, reuse, etc.). Finally, the economic and environmental performances of a product life cycle are quantitatively calculated by analyzing the dynamic material and financial flows as a whole.

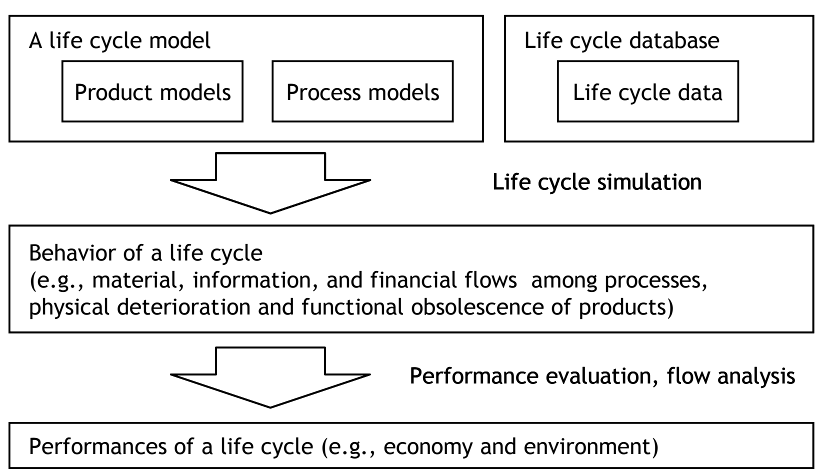

Fig. 2.2 Evaluation of life cycle performances using LCS

By conducting a LCS, a designer of a product life cycle can quantitatively evaluate the impact of life cycle design on the life cycle performance. Typical design problems supported by LCS are selection of modular structures under different end-of-life operations (Umeda et al. 2000), determination of common parts within a product platform (Fujimoto et al. 2003). Quantitative performance evaluation techniques considering stochastic phenomena in a life cycle is one of the necessary instruments for the life cycle planning (Kobayashi 2005; Kobayashi 2006).

Applications

Kondoh et al. (2005) focused on the balance of flows of material and products in a life cycle using LCS. The study defined the rate of market fulfillment as a performance indicator of the life cycle model. The study hypothesized that the performance was attributed to the demand and supply of the reusable parts and products from/to the markets. The study addressed that the market fulfillment could be improved by selecting a life cycle strategy that decreases the imbalance of flows in the life cycle.

Kumazawa and Kobayashi (2006) applied LCS to the evaluation of economic and environmental feasibility of a circulated business for personal computers. In the study, a circulated business was a product life cycle that includes the reuse of a set of products with different specifications over the multiple market segments. The study introduced product supplying rules that specified the market segment for used products as a function of value and physical lifetime in the circulated business. The study concluded that simulation supports such as LCS were helpful to evaluate the feasibility of a circulated business, in which transition of end-of-life strategies were considered.

Hata et al. (2000) introduced the concept of quality in LCS. Kato and Kimura (2004) extended the concept of quality, and simulated deterioration of the value of products. The value deterioration indicated the timing of purchase of new products by consumers independently from their physical deterioration. In the life cycle model, the value was given as a function of the elapsed time after the purchase. The simulated value deterioration models were diverse. However, each simulation did not include multiple market segments, which might have different specifications of the products regarding the value and function. This is why, the simulation could not support the design of life cycles considering the balance of product flows across multiple segments. Furthermore, external events that influenced on the value of products (e.g., obsolescence of products due to the introduction of new products in the market) were not considered.

Recent applications of LCS have focused on not only design of end-of-life processes from an environmental perspective but also design of business models. These business models explicitly include product reuse, remanufacturing, and functional upgrading service in order to gain the economic advantage by designing these activities. For instance, Fujimoto et al. (2003) proposed a method to design a service-oriented product architecture, where a set of products shares common components for multiple generations. Components of some products are reused to remanufacture other products in the same product architecture. Kumazawa and Kobayashi (2006) applied LCS to the evaluation of economic and environmental feasibility of a circulated business for personal computers, in which different end-of-life options were employed with respect to the stages in the use phase of a product life cycle. Kondoh et al. (2005) studied flows of the products in a closed-loop supply chain, in which the end-of-life options are determined by the remaining functional value of products in the market.

These business models are differentiated in terms of the contracts for the delivery of product functions (e.g., pay-per-function and shared service). Komoto et al. (2005) introduced a LCS model that dealt with such differences to analyze the distribution of profits among the multiple stakeholders. Komoto and Tomiyama (2008) focused on how to combine services available during the use phase of products (e.g., maintenance and functional upgrading services) considering both physical deterioration and functional obsolescence.

Tools

Simulation and optimization tools are crucial instruments to conduct the design of product life cycles using LCS. Commercial discrete event simulation packages are useful to develop LCS models and optimize the model performances (e.g., Arena and Delmia). Some studies developed specific tools, which are flexible in describing LCS models and reusing the model components (e.g., Umeda et al. (2000) and Komoto and Tomiyama (2008)). Such simulation tools can be integrated in commercial CAD/CAE tools (e.g., CATIA).

2.1.3 Life cycle costing and life cycle assessment

Life cycle costing (LCC) and life cycle assessment (LCA) are methodology to evaluate economic and environmental costs from a life cycle perspective, respectively. Exergy analysis (e.g., Amini et al. 2007), which evaluates exergy loss during a product life cycle, belongs to the group of LCC and LCA in context of this study as explained in the next paragraph. Their applications have a variety in terms of the resolution of analysis and the selection of performance indicators for specific purposes (e.g., Durairaj et al. 2002; Sentil et al. 2003). Volgtlaender (2001) has proposed a sustainability indicator called Eco-Value Ratio (EVR), which integrates LCA with a value description.

LCC and LCA calculate the performances of a life cycle by aggregating the average performances of sub processes in a life cycle. Furthermore, the average performance is static (referred to as life cycle inventory). Thus, LCC and LCA support analysis of the average scenario of a life cycle. Exergy analysis similarly calculates the total exergy loss during a product life cycle, although the exergy loss at each subprocess is independently calculated using thermodynamic models. In comparison with LCC and LCA, LCS calculates the performances considering interrelations among sub processes in a life cycle, and these sub-processes can include probabilistic descriptions. For instance, LCS explicitly considers influence of introduction of reuse processes on decrease of material extraction and on increase of inspection of reused products. The number of reusable products and components depends on the collection rate (a variable in the collection process) and their physical deterioration (a stochastic phenomenon at the use process)

The difference in calculating the life cycle performance characterizes the stages in a product life cycle, to which these methodologies are applied. One one hand, LCS is effective at the design stage of product life cycle, where the designers form the descriptions of products and processes (or life cycle models). It is because of that the simulation supports the designers' iterative search for alternative life cycle models. On the other hand, LCC and LCA are useful to analyze the detailed performance of a life cycle at the latter stages in a product life cycle, where the life cycle inventory is available. Furthermore, Kobayashi and Kumazawa (2006) mentioned the difference among those methodologies in terms of the scope of consideration, or system boundary. According to the study, LCS can include different market segments and respective product specifications for the performance assessment of a business with dynamic transition across markets, while the scope of LCA (and LCC) is restricted to a life cycle of product with average behavior for a single market.

2.1.4 Other horizontal integration methods

Other horizontal integration methods have been developed. The development has been mainly conducted in the field of material engineering and operational research. In the field of material engineering, for instance, van Schaik et al. (2002) developed a dynamic model of a life cycle of passenger cars. The purpose of the study is to analyze primary and secondary (i.e., recycled) flow of materials with respect to the recovery rate of the materials. The employed model included end-of-life operations such as shredding and physical separation in detail, although the model did not include services in the use phase. Ignatenko et al. (2008) extended the model so that the model could evaluate the impacts of different thermal treatment processes employed in the end-of-life operations.

In the field of operation research, distribution logistics, inventory control, and production planning have been the major interests of the researchers (Fleischmann et al. 1997). Life cycle models employed in these methods have been based on material flow analysis, stochastic mathematical programming, system dynamics, and queuing systems.

Material flow analysis methods have been developed for the analysis of the long-term economic and environmental impacts of alternative policy instruments applied to a product life cycle (e.g., Kandelaars and van den Bergh 1997; Nijkamp and van den Bergh 1997; Schwarz 2006). These methods iteratively calculate the dynamic projection of product demand proportion in a market, while calculating the corresponding economic and environmental impacts at every iteration step. Such methods can be used for the evaluation of the impacts of new policy instruments on the behavior of supply chains, as suggested in Nijkamp and van den Bergh (1997). Similar to the stochastic mathematical programming methods reviewed in the previous paragraph, the material flow analysis methods do not consider stochastic behavior of individual products.

Stochastic mathematical programming methods have been used to analyze the behavior of closed-loop supply chains (e.g., Fandel and Stammen 2004; Chouinard et al. 2008). The mathematical models used in these methods deal with the uncertainty about market demand and the proportion of products to be collected, disassembled, and reused. Such models also deal with the capacity of production process and end-of-life operations as model constraints. These models are used to optimize the total operating costs of closed-loop supply chains by considering the demand and proportion uncertainties and the model constraints. In these models, products have been treated as mass variables appearing in a set of the equations, which governs the model behavior. This is why these models are different from the model used for LCS that explicitly defines the stochastic behavior of individual products (i.e., products are finite state instances in LCS).

Georgiadis and Vlachos (2004) have applied a system dynamics methodology to the analysis of a supply chain considering product recovery. A supply chain model defined in this methodology consists of rate variables (e.g., collection rate), level variables (e.g., the number of collected products), constants (e.g., collection capacity), and their relations. As demonstrated in the study, the proposed method is useful in clarifying relations between the attributes (variables or constants) of a closed-loop supply chain and its performance indicators (e.g., a green image indicator related with the rate of manufacturing capacity expansion and with the rate of product reuse). However, the method cannot deal with quantitative evaluation of the performance of a closed-loop supply chain.

Bayindir et al. (2006) has developed a computational model of a queuing system representing a closed-loop supply chain. The model was used to investigate the level of product recovery, which is reconfigured with respect to various potential inventory control policies. The inventory control policies were characterized by the timing and the number of product orders to suppliers. The product recovery level was optimized to minimize the total holding, purchasing, and recovery costs of products with respect to the inventory control policies. The model is similar to the life cycle model used for LCS in that the model generates individual items (i.e., products) triggered by stochastic event occurrences in the market. The difference between the two models appears, for instance, in describing a variety of states of the generated products, and inventory control policies regarding the state of the products.

Hugo and Pistikopoulos (2005) focused on selection of the production sites specified by technology availability from economic and environmental criteria using a multi-objective optimization method. In the model, material and product flows followed respective conservation rules and they were constrained by the capacity of individual processes (technologies), which was controlled dynamically. It searched superior (Pareto optimum) sets of the production sites from economic and environmental perspectives. LCA-based approach was adopted to evaluate the environmental performance, while the economic performance was obtained from the costs for installation, expansion (increase of capacity), and operation of the production processes. A multi-objective optimization employed in the study is useful to find a trade-off of the conflicting performances. However, the approach did not consider the performances including end-of-life operations.

2.2 Service Modeling

Various service modeling methods have been proposed in diverse research fields such as marketing, operations management, service research, and engineering design. In addition modeling methods of product-service systems (PSSs) have been investigated by the researchers of the PSS concept. This study focuses on the service modeling methods, whose applicability is not restricted in terms of the type of products and services, because a PSS design concept includes diverse types of products and services, and because design methods and tools need to support relating these products and services as a system constituent. Following the review, the study observes the differences among these methods in describing design objects (such as products and services), specifications (such as goals of services and functions of products), correspondences between design objects and specifications, and measures to evaluate the degree of correspondences. The observation is helpful to specify the requirement of a PSS model to represent design information used in PSS design process.

2.2.1 Service modeling from marketing and managerial perspectives

Alonso-Rasgado et al. (2004) provided a comprehensive review of service modeling methods proposed from marketing and managerial perspectives. Among others, Shostack (1981) proposed a flow-chart model called *service blueprint* (See. Fig. 2.3). A service blueprint consists of *processes* and *orders* among them (i.e. process flow). Customers and service providers are also explicit design objects, because *lines of visibility* clarify the processes visible or invisible from the individual perspectives. A process flow includes branches in order to deal with the uncertainty in executing succeeding processes, which is derived from the states of customers, service providers, and external objects. A service blueprint is statistically analyzed by developing and simulating a corresponding queuing model (Berkley 1996).

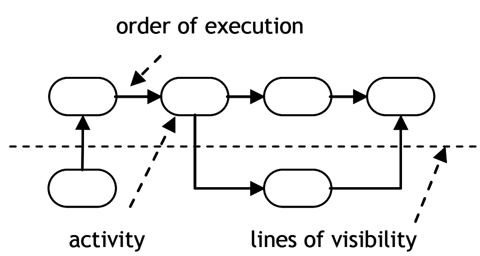

Fig. 2.3 Service blueprint after Shostack (1981)

Marca and McGowan (1988) proposed a modeling method to describe complex systems such as production systems. The method employed the structural analysis and design technique (SADT). The SADT was developed based on study about the representation of design objects for computer-aided design systems (Ross and Rodriguez 1963). The SADT was also influenced by study in the field of software engineering (Ross and Schoman 1977). The SADT became a basis of IDEF0

(Integrated Computer Aided Manufacturing Definition Language) modeling method (U.S. Air Force 1981). These methods define a system as a set of activities. An *activity*, as the atomic element, is defined as a node with input-output flows of *information*, *energy*, and *material*. In addition, *mechanisms* and *controls* are specified as subjects and constraints of activities (see Fig. 2.4). The computer-integrated manufacturing open-system architecture (CIM-OSA) reference model (Jouysz and Vernadat 1990a, 1990b) and an activity formalism proposed by Souza et al. (1998) were developed based on the SADT and IDEF0 modeling methods. Similarly, they employed an input-output based formalization to describe activities within business processes. However, their input-output formalization is different from those employed in the SADT and IDEF0 modeling methods. The formalism defines an activity as a transfer function of objects and information (from the input to the output). Furthermore, Souza et al. (1998) defined *decisions* to represent the triggering conditions to execute activities.

All modeling methods described above, however, do not explicitly define the goals of activities separately from the activities. Therefore, they cannot support the operations in a system design process, which require the description of goals. Examples of such operations include generation and refinement of the goals, embodiment of activities based on the goals, and evaluations of correspondences between the goals and the activities, which are all crucial operations in conceptual design.

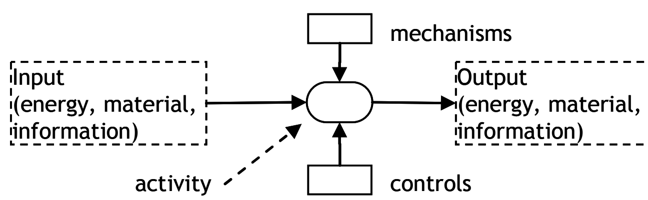

Fig. 2.4 SADT based representation

2.2.2 Service modeling for operations management

Hill et al. (2002) considered service design as process design, in which designed processes are evaluated from the perspective of service providers. For instance, the performance of a service delivery system is measured in terms of the service execution time and the efficiency of resource usage.

To integrate the perspectives of service receivers in designing new services, researchers in this field emphasized the importance of representing *what needs and wishes are to be satisfied* and *how this is to be achieved* (e.g., Edvardsson and Olsson 1996; Lovelock and Wright 1999). Clark et al. (2000) proposed the service concept, which concretizes the above what and how descriptions (see Fig. 2.5). A service concept consists of *operation* to deliver service, *experience* of customers, *outcome* of the service for customers, and *value* for customers that is obtained from the outcome against the cost.

The service concept clearly describes the relations between *operation* and those achievements (*experience* and *outcome*) and *value* as a measure to evaluate the degree of the relations (while considering against costs for customers). However, the description is not formalized and it does not consider the interdependency of individual service concepts within a system. Therefore, Goldstein et al. (2002) suggested the points of improvement for the service concept to be able to solve the problems in service design. Among them, the following points are relevant to PSS design from a systemic perspective.

- How to present service to customers as a holistic service experience rather than bits and pieces?
- How to represent the linking between the needs of customers and the design of service, while maintaining consistency with the strategic intention of service organization?

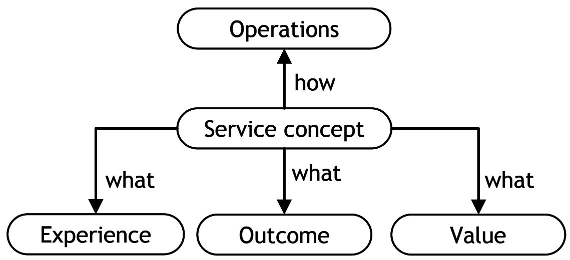

Fig. 2.5 Service concept

2.2.3 Service research about service modeling

A few researchers in service research employ model-based approaches for service design. Iacobucci et al. (2003) proposed a model of customer evaluations to examine the importance of specific attributes of a service delivery system across industrial sectors and cultural regions. The approach firstly identified attributes to be evaluated by customers from marketing literature. As is shown in Fig. 2.6, the identified attributes included *cost*, *value*, *service*, *product*, *quality*, *sales-representatives*, *easiness for doing business*, and *easiness for continuing business*. After that the authors defined a set of hypotheses that relate two attributes among them (e.g., greater perceptions of quality/cost should enhance/lower the perceptions of value). The hypotheses were statistically tested using a multi factor analysis with respect to the industrial sectors and the cultural regions. This kind of approaches can be useful to identify crucial attributes within a PSS model under specific socio-cultural contexts based on the evaluation of customers.

The theory of inventive problem solving (TRIZ) is methodology for conflict resolution in product design. The TRIZ methodology has been applied to the generation of eco-innovation idea (Chang and Chen 2004) and new service design (Chai et al. 2005). However, in order for a TRIZ-based approach to be a tool for service design, the laws and principles employed in the approach should be derived from existing good service design. This is obvious from the fact that the laws and principles of the original TRIZ (for product design) were derived from exhaustive patent analysis. Furthermore, these approaches do not formalize the description of service models, while the formalization can improve the productivity of these approaches (e.g., retrieval of the laws and principles from existing service designs with computational supports).

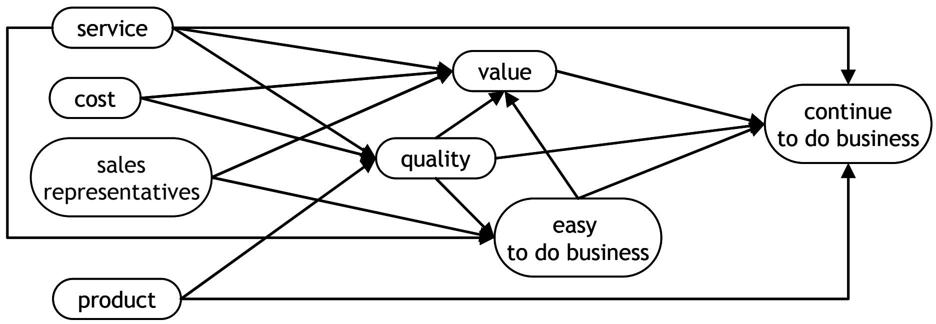

Fig. 2.6 Attributes of a service delivery system

2.2.4 Modeling methods used by PSS designers

Researches in the field of product service systems have been developing methods and tools to support sustainable PSS design (Brezet 2001; UNEP 2002; Tukker and Tischner 2006). Background of model and tool development has been summarized in Section 1.1. Here, characteristics of the modeling methods and tools are discussed.

The developed methods and tools in this field consist of design guidelines obtained from case studies. Following the guidelines, the designers use a system map to describe a PSS. An example of the system map is shown in Fig. 1.1.The system map consists of a set of stakeholders and those relations. The relations represent the flows of information, material, and energy. The designers are not instructed to explicitly define activities (preformed by the stakeholders) on the system map. Therefore, relations between the activities and the flows resulting from the activities are not clear on the system map. In terms of the performance evaluation of a PSS, the designers weigh and score environmental, economic and socio-cultural performances of the PSS. However, the designers are not instructed to define relations between the resulting scores and the system map. Thus, the designers cannot systematically improve the system map in order to improve its performances.

Morelli (2006) discussed operational tools to develop a PSS. The study proposed an interaction map, which is similar to the system map in that it consists of a network of actors in a PSS. Furthermore, the study suggested that integration of the IDEF0 method and the service blueprint method with the interaction map supports the designers to describe a PSS model using the both stakeholder-based and process (activity) -based representations.

2.2.5 Service modeling as a basis of service CAD tools

Researchers in the engineering design community regard consider service modeling as one of the essential elements to develop engineering methods and tools for design, development, and management of service (Tomiyama 1997, 2001; Shimomura et al. 2003). A service CAD tool for conceptual design of PSSs, as one of the tools, requires a service model as a means to define a PSS.

Tomiyama et al. (2004) defined service as a set of activities that delivers service contents through service channels from service providers to service receivers in a service environment, and generates values for service receivers. As is shown in Fig. 2.7, the service is described with the following service elements, viz., *service environment*, *provider*, *receiver*, *channel*, *contents*, *activity*, *aim of the service receiver's activity*, *target*, *promised goal*, *realized service*, *quality*, and *value added*. The study indicated that the value added can be evaluated in terms of the realized service relative to the promised goal, and the evaluated quality under the given service environment. The study suggested that the realized service can be measured by the degree of achievement of the receiver's state change or aim, and that the quality can be measured from multiple criteria such as capacity, efficiency and cost, etc. However, the formalization does not formulate an evaluation mechanism of the value added based on the description of activities and a service environment. Furthermore, state transitions of service receivers and other constituents in a service environment are not explicitly defined in the formalization.

The concept of a service CAD tool was proposed as one of the necessary technologies to improve the productivity of design process of business models based on the PSS concept (Tomiyama and Meijer 2003). The above service formalization is the representation to describe the elements of PSSs. However, the computability of the representation has not been discussed and concrete functionalities of a service CAD tool have not been established.

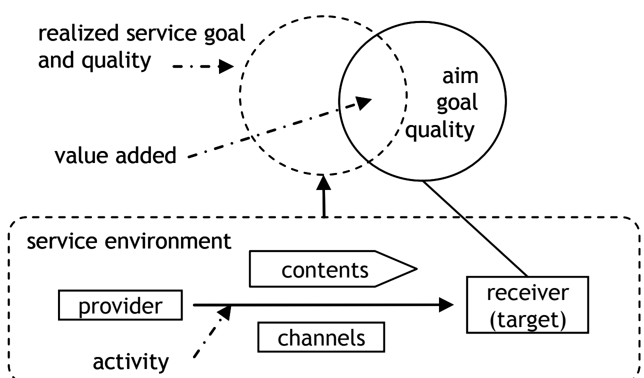

Fig. 2.7 Service formalization

Service Explorer supports product design in the early design phase (Arai and Shimomura 2004, 2005; Sakao and Shimomura 2007). The definition of service adopted in Service Explorer is the same as the Tomiayama’s definition above. Service Explorer's main functionality is to identify the attributes of service channels and service contents from the subjective evaluation about the service by service receivers. Functions and attributes of service contents and service channels are intermediate concepts that relate the attributes of products (entities) with the evaluation by service receivers. For this reason, Service Explorer employs a direct graph representation called Serviset (Hara et al. 2006) As is shown in Fig. 2.8, Serviset consists of receivers' state parameters (RSPs) as the root of a Serviset, and function parameters of the service contents (CoPs) and service channels (ChPs) as intermediate elements, and attribute parameters of entities as elements at its leaves (APs). Service Explorer takes the quantitative score of RSPs as input and it identifies the degree of importance of CoPs and ChPs by weighting the scores of RSPs through the propagation of quantitative values in the tree. This weighting procedure determines the importance of each attribute parameter. In Service Explorer, an activity is defined by a set of RSPs evaluated by the service receivers appeared in the activity. However, the representation cannot describe the consequences of activities that change the value of parameters of the elements, which are related with the RSPs in the activities through a Serviset. Therefore, Service Explorer cannot evaluate specific activities that dynamically maintain and improve APs, CoPs and ChPs, which eventually influence on RSPs.

Having described the characteristics of the service modeling method employed in Service Explorer, its characteristics as a service CAD tool are discussed as follows. As a visualization tool, Service Explorer visualizes the aims of service receivers and the attributes of service channels and service providers, and these connections. Activities in a service model on Service Explorer are dealt as frames that organize a set of quality criteria to be focused. It cannot deal with state transitions on products and users occurred as a result of activities. As an evaluation tool of service, Service Explorer is equipped with a functionality to calculate the importance of attributes of products and service providers based on the subjective evaluation of service by users. However, it cannot evaluate service based on activities and a service environment. As a design tool, Service Explorer has difficulty in verifying a service model under development, and in directing the designers to improve a service model.

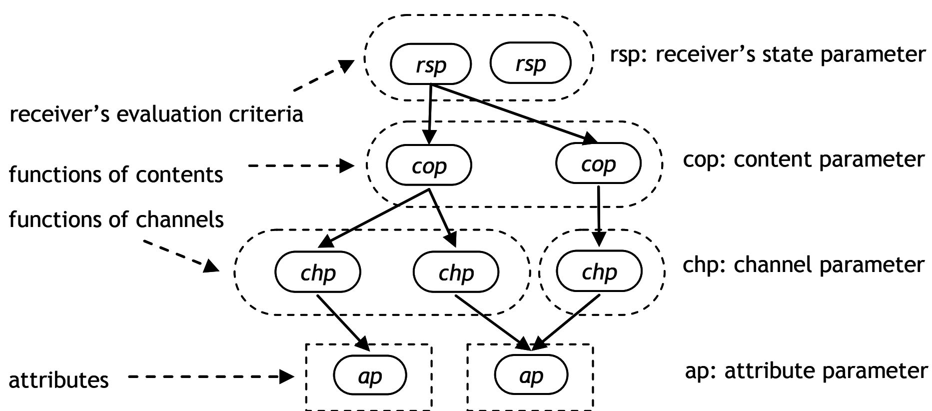

Fig. 2.8 Serviset

Karni and Arciszewski (1997) proposed a tool for the conceptual design of production and operations systems, such as service systems for after sales, in which maintenance and repair services are the design objects. The tool defines generic attributes (as variables) to describe the knowledge in conceptual design of such a system. The attributes are classified into goal types (needs to be satisfied), environment types (external factors to be considered) and structure types (design parameters to represent a system). This classification is considered as separation of the design objects and the specifications within the system description. The tool supports the conceptual design by providing a number of formal operations, or design knowledge transmutations, to modify the list of attributes and their values. Although the tool describes design parameters and those relations generated in the conceptual design phase, the generic representation cannot provide a means to use the information specific to products (e.g., physical/functional life time of products, module structure) and services (e.g., costs and conditions of maintenance and repair activities) for PSS design. Furthermore, the tool cannot incorporate evaluation mechanisms to assess the quality of the generated design guided by the formalized operations.

2.3 Comparative analysis of the reviewed models

In this section, the usefulness of life cycle modeling methods and service modeling methods in PSS design process is discussed.

Life cycle modeling methods for the evaluation of PSS design concepts

Characteristics of the modeling methods and tools for design of life cycles reviewed in Section 2.1 are summarized as follows.

- Life cycle simulation (LCS) and corresponding modeling methods are useful in designing life cycles considering physical and functional deteriorations of products, and decisions of product users regarding selection of products and those of manufacturers at their end-of-life operations. These deteriorations and decisions in LCS are treated as stochastic phenomena by including probabilistic variables in their life cycle models. LCS has been developed for the comparison and analysis of the designs of life cycles at an early product design stage, while accepting a certain degree of the uncertainty due to these stochastic phenomena.
- Life cycle assessment (LCA) and life cycle costing (LCC) methods are useful in identifying the processes in a product life cycle, which have major impacts on the performances. These methods have been developed with a motivation to analyze the performances of existing life cycles, assuming the availability of quantitative inventory information. Furthermore, the methods are restricted to evaluation of life cycles with a specific interest (i.e., LCA for environmental performance and LCC for economic feasibility).
- Some dynamic models in Section 2.1.4 are also useful in analyzing dynamic and stochastic behavior in a life cycle of products. A set of equations governing the behavior can express such behavior as material flows. However, it cannot track the behavior of individual products, which are handled in LCS-based models.

Furthermore, these dynamic models do not support addition and removal of the governing equations during the analysis (i.e., scenario changes). On the contrary, LCS-based models allow changes of end-of-life options during a product life cycle by adding or removing processes in it.

Based on the review, it is suggested that LCS technique and dynamic modeling methods are useful in PSS design considering stochastic behavior in a life cycle of products. Multiple optimization methods can be integrated to deal with conflict among stakeholders in a business model from multiple performance perspectives.

PSS design process is partly considered as an activity to define a PSS model. In this activity, parameters of individual products and services are defined. LCS technique, in comparison with other dynamic models in Section 2.1.4, is an appropriate modeling and evaluation technique when services depend on the individual state of products and product users.

Service modeling methods to represent PSS design information

As introduced in Section 1.3., design information used in design activity should include design objects, specifications, and correspondence between them. The reviewed life cycle modeling methods, however, do not sufficiently provide such information. For instance, life cycle simulation (LCS) requires product and process models as design objects, and the simulation evaluates the model performances as design specifications. However, the performance indicators are nothing more than scalar or vector values, and they do not provide sufficient information to support building (rather than evaluation) of product and process models.

In comparison, the review about service modeling methods presented in Section 2.2 has shown that elements in those service models can be classified into design objects and specifications in PSS design, and correspondence between them as follows.

- Design objects in a service model are described in terms of activities (processes or operations) and constituents (stakeholders and artifacts) in a service environment.
- Specifications in a service model are described in terms of goals and quality criteria.
- Correspondences between the design objects and the specifications are described in terms of realization of activities (as experience), results of activities (outcome, delivery of service contents, or resulting state transitions of the design objects), and quality derived from the attributes of design objects.
- Degree of the correspondences is measured in terms of the realization of goals and the values of quality. To construct a function of a service model to evaluate the degree of correspondences, each goal and quality criterion should have references to the execution of desired activities and states (and their transitions) of the constituents in a service environment.

To represent design information used in PSS design process, the current system modeling method used in PSS designers (Section 1.1.2 and Section 2.2.4) is not sufficient. The reason of the insufficiency is that it cannot describe all of the three types of design information listed at the discussion above.

Among the reviewed service modeling methods, the service formalization and the service modeling method employed in Service Explorer in Section 2.2.5 developed in the field of engineering design includes all of the three types of design information listed above.

2.4 Conclusions

In this chapter, methods and tools for life cycle modeling and service modeling have been reviewed. The review has focused on the potential usage of these methods and tools in PSS design process.

Some of the reviewed life cycle modeling methods and tools can be used for the evaluation of PSSs. LCS in Section 2.1.2 and dynamic methods in Section 2.1.4 deal with stochastic phenomena in a product life cycle. They are useful in designing PSSs, because the performance is derived from the parameter values of products, product users, and manufacturers, which are explored during the design process. Moreover, the capability of LCS to track the behavior of individual products, product users, manufacturers, is useful in evaluating PSSs, in which diverse services are delivered to individual product users and diverse end-of-life operations are applied to individual products.

However, the reviewed life cycle modeling methods and tools cannot support building of these models (rather than evaluation of these models), which defines parameters of products, product users, and manufacturers, and processes (ore services) to relate these parameters.

The reviewed service modeling methods compensate the reviewed life cycle modeling methods in the model building process. Considering the model building process as a design activity in PSS design process, service modeling methods should explicitly represent design information classified into design objects, specifications, and correspondence among them. The current modeling methods used by PSS designers (Section 1.1.2 and Section 2.2.4) are not sufficient, because these methods do not explicitly classify design information used in PSS design process into three types.

Among the reviewed service models developed in the field of engineering design (Section 2.2.5) include all three types of design information. However, investigation on these methods is necessary for the development of service CAD/CAE tools for PSS design. Especially, study of formal methods, based on these service modeling methods, to systematically build PSS models, is necessary. Furthermore, these PSS models can be used for the evaluation using the reviewed life cycle modeling methods.

3 *Service CAD* for systematic PSS concept design

In the previous chapter, related work about service modeling methods and life cycle modeling methods has been reviewed. On one hand, the review has provided the answers to research question RQ1a. On the other hand, the review specifies functions of a CAD/CAE tool for PSS design. The tool is crucial to study design information used in the PSS design process under computer-aided environment (see RQ1b, RQ2a, and RQ2b). Of those methods, the reviewed service modeling methods provide descriptive representations of design information used in PSS design processes (see Conclusions in Section 2.4). Formalization of these descriptive representations is crucial to develop a CAD tool for PSS design. In this chapter, *Service CAD* is proposed as a prototype CAD tool for PSS design, following the development of a formal representation of PSSs. Especially, *Service CAD* supports designers to generate PSS design concepts. It first supports designers to evaluate PSS design concepts in terms of the property of its constituents. Second, using the result of the first support, it supports designers to add new elements (e.g,. products and services) to PSS design concepts by suggesting candidate elements. Utility of these supports are observed through two illustrative examples. This chapter is concluded with remarks regarding organization and utilization of design information for systematic generation of PSS design concepts under computer-aided PSS design environment.

3.1 Introduction

Conceptual design is a task in a design process to hierarchically decompose the overall function of products into elemental functions and find physical principles to meet elemental functions (Pahl and Beitz 1996). Since the result of conceptual design is structural, behavioral, and functional descriptions about the overview of products, the quality of this task determines the approximate performance of products. To improve the quality of this task, few computer aided design (CAD) tools have been developed (e.g., Tomiyama et al. 1993; Welch and Dixon 1994; Umeda et al. 1995; Bracewell and Sharpe 1996; Yoshioka et al. 2004). In this chapter, a CAD tool for conceptual design of PSSs is proposed. The tool is referred to as *Service CAD*. The PSS design process using *Service CAD* is also presented.

Comparison of the structure of design information in product design processes and in PSS design processes is useful to clarify the functions of *Service CAD* (see Fig. 3.1). In product design processes, designers define physical principles to meet specified function requirements. The physical principles consist of structural and behavioral information. The CAD tools reported in the work quoted at the above paragraph have utilized qualitative descriptions about function, behavior, and structure. In PSS design processes, designers define activity to meet specified goal and quality, and define environment, under which the activity is realized (see Section 2.4). In defining this kind of information in PSS design processes, one of the expected functions of *Service CAD* is to complement design information about activity and environment against specified goal and quality. Such function has not been proposed and offered by other service CAD tools (e.g., Service Explorer).

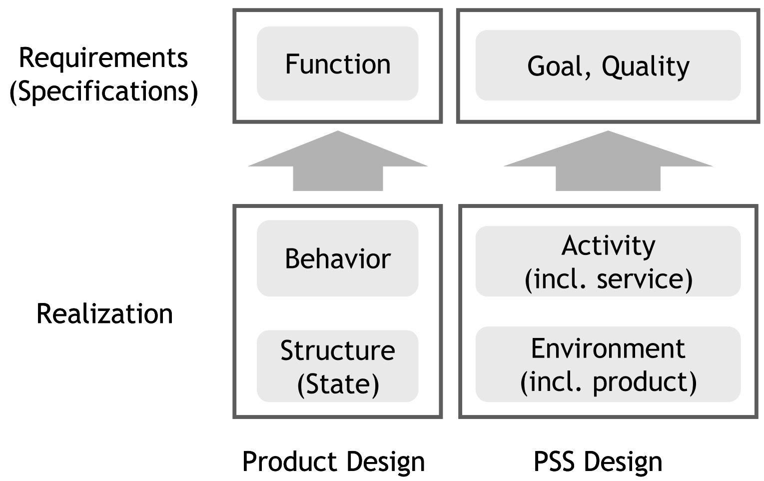

Fig. 3.1 Comparison of the structure of design information in product design and PSS design.

To develop *Service CAD* with such a function, a formal PSS model to represent the design information is necessary. For the development of a formal PSS model, this study accepts the following definition of service and a set of assumptions from the literature about service modeling reviewed in Section 2.2.

- *Service* is defined by a set of activities to deliver contents from providers to receivers with channels in environment. (Tomiyama et al. 2004). This definition implies that service itself is described in terms of activities, which is common in other service modeling methods (Chapter 2.2). Furthermore, the definition also implies that service should be related with other types of design information so that the service is designed and analyzed based on them (and visa versa).
- *Environment* (E) consists of *providers* (P), *receivers* (R), *channels* (Ch), and *contents* (Co), or formally E(P, R, Ch, Co) (Tomiyama et al. 2004).
- *Quality* is specified and evaluated by receivers in terms of the parameters of channels and contents (Sakao and Shimomura 2007). This assumption indicates descriptions of parameters of members of environment are necessary to relate quality with environment.
- *Goal* is specified by receivers and realized by service or by state transitions of receivers (Tomiyama et al. 2004). This assumption indicates first that goal has relations with either service or environment. It indicates second that descriptions of state of members of environment are necessary to relate goal with environment.

Although the definition of service and some of these assumptions are not formal but descriptive, they specify the types of design information to describe elements of PSSs and their relations. Using these descriptive forms, designers can express products and services as the constituents of PSSs, and goals and quality as the specifications (requirements) of PSSs. However, few studies have addressed how this information ought to be stored, organized, and utilized at a PSS design process supported by service CAD tools.

The formal PSS model proposed in this study is inspired by categorization of service (Tomiyama et al. 2004) and PSS types (Tukker and Tischner 2006; Tukker and van den Berg 2006), which are shown in Table 3.1 and Table 1.1. They are not formal but descriptive. This study tries to formalize these categorization and types.

Table 3.1 Examples of categorization of service and PSS types.

	Type	Characteristics	Examples
Tomiyama et al. (2004)	Enabling service	Service that makes the service receiver to do something.	Rental car(to trip), bank (to obtain cash), internet-based airline ticket sales system (to book tickets)
	Enhancement service	Service that improves the quality perceived by the service receiver	House cleaning (to improve cleanness), elevator maintenance (to improve security and safety)
	Proxy service	Service that represents the service receivers	Tax consultant, travel agent
	Message service	Service that delivers information	Broadcasting, management consulting, remote medical diagnosis
	Massage service	Service that causes physical effects	Massage treatment, airlines
Tucker and Tischner (2006)	Product-oriented service	Ownership of products is transferred to the customer, but additional services are provided.	Additional maintenance and upgrading contracts
	Use-oriented service	Ownership of products remains at the manufacturer, but functions of products are sold.	Sharing service, pay-per-function based contract
	Result oriented service	Products are replaced by services	Voicemail replacing answering machines

The formal PSS model proposed in this study is based on set theory, which formalizes binary relations between two mathematical objects. Elements of design information comprising a PSS, and types of these elements can be treated as mathematical objects. The types of design information initially considered are environment (E), activities (A), goals (G), and quality criteria (Q). To use the formal PSS model in the conceptual design of PSSs, correspondences of the design information belonging to different types have to be defined. Thus, to develop the formal PSS model, a set of functions to define such correspondences is described in Section 3.2. These correspondences can be used to evaluate PSSs in the conceptual design, and systematically identify possible modifications of PSSs. The second task is to classify design information with special properties (e.g., *executed* activity, *realized* goal, *enhanced* quality, etc.) regarding the types. Finally, a calculation method of these properties considering additional internal structure of the design information is developed.

In Section 3.3, two design supports based on the formalization is described. The first design support identifies the properties of the design information defined in Section 3.2. The second design support helps designers introduce new activities (services) into a PSS. The activities modify the properties of elements in the PSS. The support is realized by selecting preliminary stored activities, which are related to elements belonging to the other types of design information. The support is also used to add the other types of elements to the PSS. For instance, parameters are added to the products in a PSS.

In Section 3.4, *Service CAD* is proposed as a systematic PSS modeling tool with the design supports described in Section 3.3. After describing its architecture, a method to generate PSS design concepts using *Service CAD* is presented. Its implementation is presented at the end of this section.

In Section 3.5, usefulness of *Service CAD* is demonstrated with two illustrative examples. The example presented first explains an entire PSS concept design process presented in Section 3.4. The example is prepared for the analysis of three different (product-, use-, and result-oriented) PSS types shown in Table 3.1. Functional upgrading service for computer embedded systems is chosen as the main service included in the example, because complex products such as computer embedded systems require service during the life cycle in order to maintain the performances and adopt themselves to the specific needs of users, and because various service contents, channels, and providers within a PSS are necessary to form alternative design concepts. The example presented second includes products and services offered by manufacturers of medical instruments (e.g., magnetic resonance imaging (MRI) scanners, image processing tools) as the core elements of a PSS design concept used in the healthcare industry. The reason is that existing services by the manufacturers have been diverse in terms of ownership structure, service contracts, and machine selections according to the needs of machine owners, doctors, and patients (Scott and Atlas 2004; Sistrom and McKey 2005; Levin et al. 2008). It is therefore of interest for PSS designers to analyze the information about current products and services offered by manufacturers is systematically organized and utilized for PSS design.

In Section 3.6, characteristics and limitations of *Service CAD* are described, and future research issues regarding the improvement of *Service CAD* are discussed.

In Section 3.7, the summary of this chapter is described and the conclusions are drawn by proposing a systematic method to organize and utilize design information for computer-aided PSS concept design.

3.2. A formal representation of PSSs

In this section, a formal representation of design information to describe a PSS for its conceptual design process is proposed. This representation is based on the definitions and assumptions given in Section 3.1.

First, design information is classified into goals, quality criteria, activities, and environment. Considered that the design information can be treated as a set of countable mathematic objects, it is defined by four sets; G (goals), Q (quality criteria), A (activities), and E (environment). A member of G, Q, A, and E are g, q, a, and e, respectively.

$$g \in G \quad (3.1)$$

$$q \in Q \quad (3.2)$$

$$a \in A \quad (3.3)$$

$$e \in E \quad (3.4)$$

Definition of service

Service is defined by a set of activities to deliver contents from providers to receivers with channels in environment. (Tomiyama et al. 2004). This definition implies that service is a member (members) of activities. Conditions of service are specified by members of environment. Furthermore, consequences of service are specified by the delivery of service content. Assumed that the delivery of service content is a realization of service goal, relations among, goal, activity, and environment are formalized by introducing some mappings among goals *G*, activities *A*, and environment *E*. First, *executable* is defined by a mapping from activities *A* to environment *E*. Second, *realize* is defined a mapping from activities A to goals G. When a designer defines design information $G' \subset G$, $E' \subset E$, and $A' \subset A$, relations among G', E' and A' are described in Fig. 3.2. Here realized service $M' \subset G$ is defined in Expression 3.5.

$$M' = G' \cap \mathrm{realize}(A' \cap \mathrm{executable}(E')) \quad (3.5)$$

Difference between product design and PSS design is derived from the dynamic property of design objects (i.e., behavior of products and that of product users). In product design, the behavior of a product is often predictable with analysis based on physical rules and simulation techniques. Therefore, the difference between the prediction and the actual behavior can be decreased by applying these analytical techniques to the design process. In contrast, prediction of the behavior of product users is difficult due to lack of the applicability of scientific findings.

Members of environment

As given in one of the assumptions in Section 3.1, environment consists of four types of elements; providers, receivers, channels, and contents. In other words, a member of environment *E* is a member of at least one of P (providers), R (receivers), Ch (channels), and Co (contents). These types are not mutually exclusive. For instance, an intermediate agent has double characteristics of a receiver and a provider (Sakao and Shimomura 2007). A car is considered as a content, when the ownership of the car is delivered (as a gift). The same car is considered as a channel, when the receiver of the car is a taxi driver, and the car is used to deliver mobility to passengers. (In this example, mobility is the content of the taxi service.) This is the cause of difficulty for designers to categorize them into a member of P, R, Ch, or Co. Consideration of the relations between these four types and environment is used to form Expression 3.5.

$$e \in E = P \cup R \cup Ch \cup Co \tag{3.6}$$

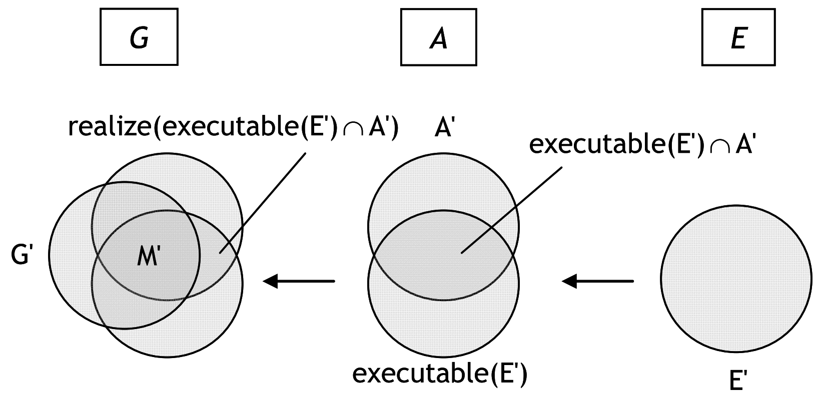

Fig. 3.2 Relations among goals, activities, and environment based on the definition of service.

Introduction of parameters

The definition of service does not explicitly define parameters of members of environment. However, the necessity of the parameters is implied in literature in the field of service engineering. For instance, goals are realized by state transiton of environment (Tomiyama et al. 2004). Quality is evaluated (related) in terms of the parameter of channels and contents (Sakato and Shimomura 2006). For this reason, parameters of a member *e* are defined by PRM_e. The relation between PRM_e and E is described with Expression 3.7.

$$PRM_e = parameter_e(E) \tag{3.7}$$

where, $parameter_e$. is a funciton to obtain all parameters belonging to e from environment E. A set of parameters PRM, which belong to all members of environment is described with Expression 3.8. A member of PRM is defined by prm (Expression 3.9).

$$PRM = parameter(E) \tag{3.8}$$

$$prm \in PRM \tag{3.9}$$

For the sake of simplicity, a relation between two members of environment is described with a parameter shared by the members.

Introduction of parameters restricts executable activities under given environment. Given a mapping *p-executable* from parameters to activities, relations among parameters, activities, and environment are shown in Fig. 3.3. The relation between executable activities considering the member of given environment and those considering the parameters of these members is defined by

Expression 3.10. Consequently, realized service M' considering these parameters is defined by Expression 3.11.

$$\text{p-executable}(\text{parameter}(E')) \subseteq \text{executable}(E')) \quad (3.10)$$

$$M' = G' \cap \text{realize}(A' \cap \text{p-executable}(\text{parameter}(E'))) \quad (3.11)$$

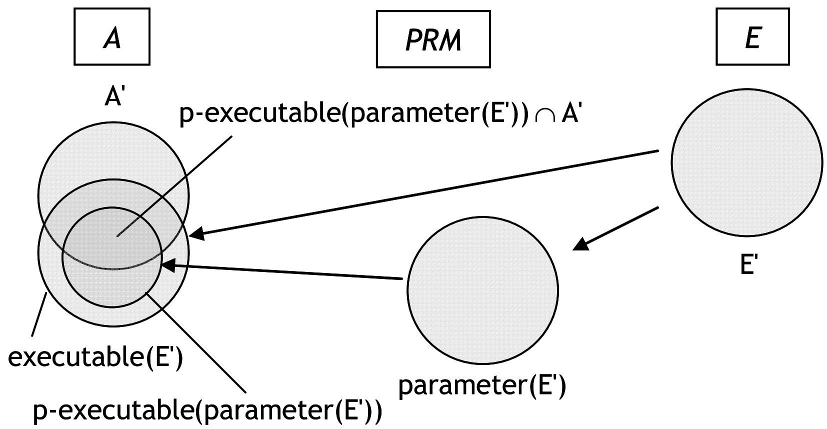

Fig. 3.3 Relations among activities, parameters, and environment in terms of execution of activities

Measurement of quality

Comfort during the stay at a hotel room can be considered as a quality criterion for tourists. Measurement of the comfort is difficult, unless tourists actually stay the hotel. The measurement can be subjective, because some tourists may evaluate the comfort in terms of whiteness of the bed linen, while others may evaluate it in terms of the amount of dust on the floor.

In order to formally define relations between quality criteria Q and parameters PRM, and activities A, some mappings are defined. First, *evaluated* is defined by a mapping from activities *A* to quality criteria *Q*. This mapping means that the members of Q are evaluated when activities *A* are executed (e.g., stay at a hotel). Second, *related* is a defined by a mapping from parameters PRM to quality criteria *Q*. This mapping means that the members of Q are evaluated as functions of PRM (e.g., whiteness of the bed linen and comfort). When a designer defines design information $Q' \subset Q$, $E' \subset E$, $A' \subset A$, and mappings *parameter*, *p-executable*, *related*, and *evaluated*, relations among Q', E' and A' are described in Fig. 3.4. Using these relations, measurable quality criteria defined by the designer Q_{eerd}, is determined by Q', PRM' and A'.

$$Q_{eerd} = Q' \cap \text{related}(PRM') \cap \text{evaluated}(A' \cap (\text{p-executable}(PRM'))) \quad (3.12)$$

Specification of goals and quality criteria by receivers

A PSS can include multiple stakeholders (Chapter 1), or multiple receivers in terms of the formalization in this chapter. Thus, when the designer of a PSS defines goals and quality criteria, he/she should also define receivers that specify these goals and quality criteria. This relation is defined by mapping *specify-goal* and *specify-quality* from environment to goals and to quality criteria, respectively. When a designer define receivers in environment $R' \subseteq E'$, goals G', quality criteria Q', and these two mappings, the possible classification of members of goals G and quality criteria Q based on these mappings is given as shown in Fig. 3.5. Fig. 3.5 implies that some goals and quality criteria are not defined by the designer but specified by receivers. It also implies goals and quality criteria defined by the designer but not specified by receivers. When receivers' specifications of goals and quality criteria are considered, the intersections in Fig. 3.5 can replace G' and Q' in Expressions 3.5, 3.11, and 3.12.

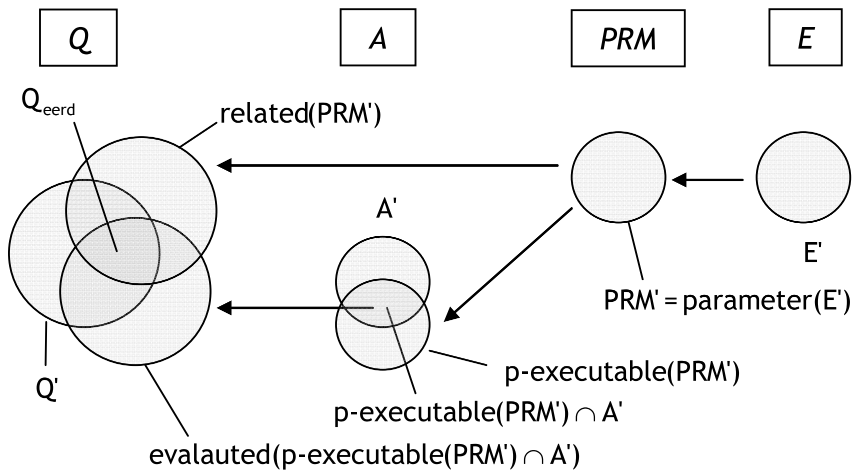

Fig. 3.4 Relations among quality criteria, activities, parameters, and environment for the identification of measurable quality criteria

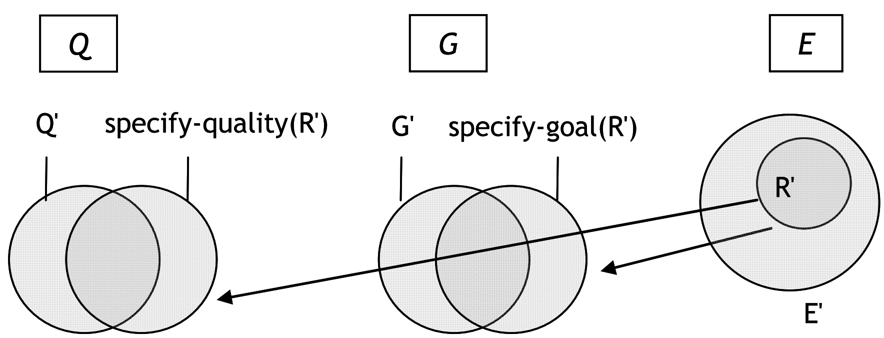

Fig. 3.5 Classification of goals and quality criteria considering receivers in environment to specify them

Hierarchical structure of goals

A designer defines functions of products and decomposes them into sub-functions. Similarly, members of goals specified by a designer G' can constitute a hierarchical structure. Assuming the existence of multiple receivers to specify goals, members of goals can constitute multiple hierarchical structures. Given *roots* as a mapping from G to G to define the roots of hierarchical structures, and *leaves* as leaves of them, $\text{roots}(G')$ can be used in place of G' in Fig. 3.5, and leaves(G') in place of G' in Expressions 3.5 and 3.11.

Enabling service

For tourists to do scuba diving in a small island, they may need to rent scuba gears. They may need to get license to do so at school. Renting scuba gears and receive education themselves do not provide experience in deep sea. However, they are necessary to have the experience.

Enabling service is a member of activities, but it is not the member of the activities that directly realize goals (see Expressions 3.5 and 3.11). This service rather changes the state of environment to make members of activities that potentially realize goals executable.

In order to identify this service based on the formalization, two types of activities should be identified. The first type is the activities to be enabled (e.g., scuba diving). The second type is the activities to enable the first type of activities (e.g., education and rental service). Pairs of a member of the activities belonging to each type (a_{ena}, a_{ena^*}) are found with some mappings and their inverses. First, *consequences* and *conditions* are given as mappings from A to PRM. *consequences* defines the members of PRM influenced by execution of the member of A, while *conditions* defines the members of PRM used to check whether the members of A are executable or not.

Assumed G' and PRM' are given and each element of the pair (a_{ena}, a_{ena^*}), is the sole member of sets $A'_{ena} \subseteq A'$ and $A'_{ena^*} \subseteq A'$, respectively, the pair (a_{ena}, a_{ena^*}) is the elements of an enabling service when the following three sets are non empty sets. These expressions are illustrated in Fig. 3.6.

$$G' \cap \text{realize}(A'_{ene^*} \cap (\text{p-executable}(PRM')^C)) \quad (3.13)$$

$$G'^C \cap \text{realize}(A'_{ene} \cap (\text{p-executable}(PRM'))) \quad (3.14)$$

$$\text{consequences}(A'_{ene}) \cap \text{conditions}(A'_{ene^*}) \quad (3.15)$$

Expression 3.13 means that a_{ena^*} can realize goals but not yet executable. Expression 3.14 means that a_{ena} does not realize goals but executable. Expression 3.15 means that a_{ena} influences a parameter when executed, and execution of a_{ena^*} depends on the parameter.

Enhancing service

Comfort of tourists during their stay at a hotel room can be enhanced by additional cleaning of the bed linen and the floor before their stay. These cleaning services are performed without influence the state of tourists.

Similar to enabling service, enhancing service is a member of activities, but it is not the member of the activities that directly realize goals (see Expressions 3.5 and 3.11). This service rather changes the state of environment that influences the evaluation of quality.

Assumed a_{enh} is the sole member of $A'_{enh} \subseteq A'$, a_{enh} is an enhancing service when the following two sets are non empty sets. Expression 3.17 means that a_{enh} does not realize goals but executable. Expression 3.18 means that a_{enh} influences a parameter when executed, the parameter is related to quality criteria, which is measurable and defined by the designer.

$$G'^{C} \cap realize(A'_{enh} \cap (p\text{-}executable(PRM'))) \quad (3.17)$$

$$Q_{eerd} \cap related(consequences(A'_{enh})) \quad (3.18)$$

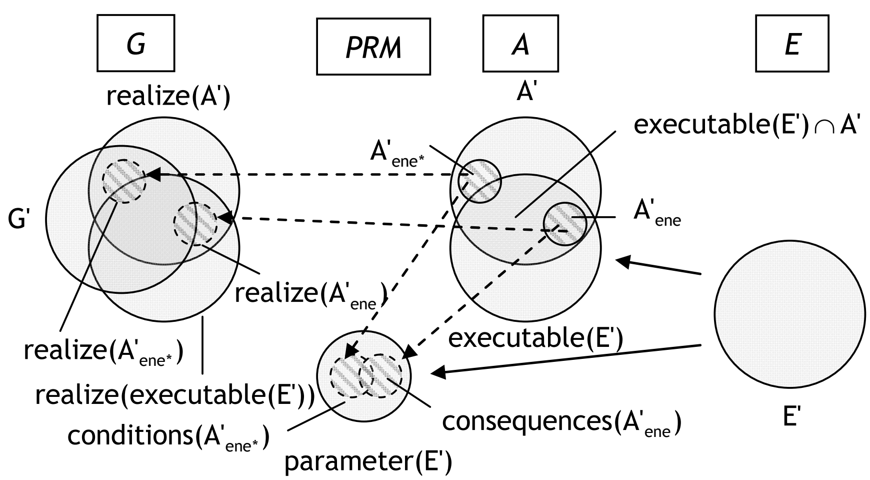

Fig. 3.6 An illustration of the identification of enabling service.

3.3 Model-based PSS design supports

In this sub section computational supports for conceptual design of PSSs based on the formalization defined at the previous subsection are presented. On one hand, the formalization provides logics to evaluate the performance of a PSS model currently under development (evaluation algorithm). On the other hand, PSS models defined using the formalization in advance are used as sources for suggestions of activity that increases the performances of a PSS model currently under development in terms of the above defined value added (suggestion algorithm).

A calculation method for execution of activities

Before describing these two algorithms, a calculation method for execution of activities is introduced. Among the mappings introduced in the previous subsection, calculation of *executable* (a mapping from environment E to activities A) and *p-executable* (a mapping from parameters PRM to activities A) should be performed dynamically. The reason of this is that the value of parameters, which is not defined in the proposed formalization, can change after execution of activities, and that new members of environment can be introduced (existing members of environment can be removed).

In addition to the formalization in the previous subsection, a calculation of these mappings with respect to an activity in a sequence of activities is introduced. (Other methods for the internal structure of activities and the representation of value space of parameters can be connected to the formalization presented in the previous subsection.)

The sequence of activities is an internal structure of activities defined by the designer A' (Expression 3.18). Furthermore, a qualitative and relative ordering method to define the value space of a parameter (Forbus 1984) for the calculation of executing activities.

$$\mathrm{seq}(\mathrm{A'}) := [\mathrm{a}_0, \mathrm{a}_1, \ldots, \mathrm{a}_n] \text{ where } \mathrm{a}_i \in \mathrm{A'}\ (i = 0, 1, \ldots, n) \tag{3.19}$$

The conditions and consequences of executing an activity *a* are defined by *conditions* and *consequences*, which are mappings from A to PRM, defined in the previous subsection. In evaluating whether an activity is executable or not with consideration of the value of parameters, comparisons between two values are made. The first value represents the current value of parameters. The second value is specified by the conditions. In considering influences of the execution of an activity on the value of parameters and on the member of environment, consequences of an activity are classified into seven types. (1) generation and (2) deletion of a member of environment *gen*(*e*) and *del*(*e*), (3) generation and (4) deletion of relations between members of environment *gen*(*rel*) and *del*(*rel*). (5) increase, (6) decrease, and (7) change of the value of parameters (*inc*(*prm*), *dec*(*prm*) and *set*(*prm*)). For the sake of simplicity, a relation between two members of environment is described with a member of parameters shared by the members of environment.

3.3.1 Evaluation algorithm

This algorithm calculates the mappings of four types of design information Q', G', A', and E', which represent a PSS model, defined by a designer. The calculation is performed with respect to each activity in a sequence of activities. Calculation of two types of mappings *executable* and *p-executable* depends on the order of activities to be executed. By running the evaluation algorithm on a PSS model, the characteristics of the PSS model are checked from the following evaluation criteria.

- All goals and quality criteria defined by the designer G' and Q' are specified by at least one of the receivers in environment. When hierarchical structures of the goals are assumed, $roots(G')$ is considered instead of G'. This is evaluated before the execution of activities.
- All quality criteria defined by the designer Q' are related with parameters of members in environment. This is evaluated before the execution of activities.
- All activities in $seq(A')$ are executable step by step in environment *E*. This depends on the order of activities to be executed.
- All goals and quality criteria defined by the designer G' and Q' are realized or evaluated by activities defined by the designer A'. When hierarchical structures of the goals are assumed, $leaves(G')$ is considered instead of G'.
- All members of environment and all parameters of the members are justified. (In other words, they are conditions and consequences of executed activities or related with quality criteria.

The evaluation algorithm is a procedure to label the members of G', Q', A', E', and PRM' following those evaluation criteria. The procedure is shown in Fig 3.7. The types of labels, the labeling conditions, and those interpretations are described in Table 3.2.

Table 3.2 Labels, labeling conditions and interpretations

Types and labels	**Labeling conditions and interpretations**
a • *executed* • *unexecutable*	-- *a* is labeled *executed* when *a* is executable according to the calculation method in p.45. When *a* is not executable, it is labeled *unexecutable*. These two labels are mutually exclusive.
g and *q* • *targeted* • *realized* • *evaluated*	-- *g* and *q* are labeled *targeted*, when they are members of *specified-goal* or *specified-quality* of initially existing members of environment (see. Fig. 3.5). -- *g* is labeled *realized*, when it becomes the member of the realized service goal *M* (see. Expression (3.5)). -- *q* is labeled *evaluated* when it becomes the member of q_{eerd} (see. Expression 3.12)
e and *prm* (incl. relations) • *condition* • *unsatisfied* • *related* • *justified* • *influenced*	-- *e* and *prm* are labeled *condition*, when they are *conditions* of *executed* members of activities in *seq*(*A'*). Condition elements are also -- *e* and *prm* are labeled with *condition* are also labeled *unsatisfied* when they do not satisfy the conditions of the activities. Unsatisfied elements therefore become the causes of *unexecutable* members of activities. -- *prm* is labeled *related*, when it is a member of PRM', whose mapping with *related* to Q' includes members of *evaluated* quality criteria. -- *e* and *prm* are labeled *justified* when they are at least one of the members of condition elements or related elements. Justified elements are necessary design information to constitute the PSS model. In other words, removal of unjustified elements from the descriptions of service environment *E* does not influence on the model performance. -- *e* and *prm* are labeled *influenced*, when they are deleted members of E', deleted relations (as members of PRM'), and members of PRM', whose value change during the execution of members of A' following *seq*(*A'*).

The members of goals, quality criteria, activities, and environment (and parameters of the members of environment) to constitute a PSS model are given as input of the procedure. Furthermore, a sequence of activities and the initial value of parameters of the members of environment are given as the input. The procedure iteratively evaluates members of the activities following the given sequence. If the members are executable, the value of respective members of parameters is increased, decreased, or changed. After that model elements are labeled according to the conditions shown in Table 3.2. This iteration process continues until an activity instance in *seq*(*A*) is labeled *unexecutable*, or all the activity instances are labeled *executed*.

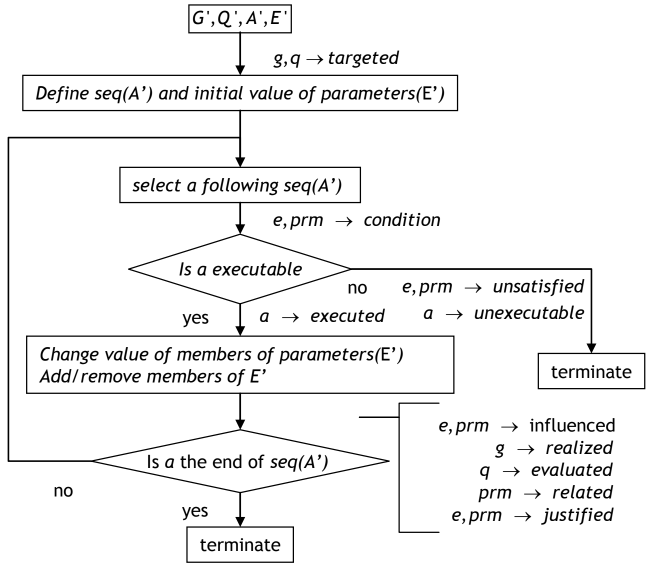

Fig. 3.7 The evaluation algorithm and corresponding labeling procedure

Figure 3.8 (a) shows the relations among the sets of the labeled elements with respect to goal *G*, quality criteria *Q*, activities *A*, and parameters *PRM*. The relations are compared with the ideal relations specified by the formulation in the previous section shown in Fig.3.8 (b). During the design process, labels of the elements in a PSS model under development show the relations typically described in Fig. 3.8 (a). Therefore, the algorithm offers designer of PSSs to systematically remove unnecessary descriptions of parameters and members of environment.

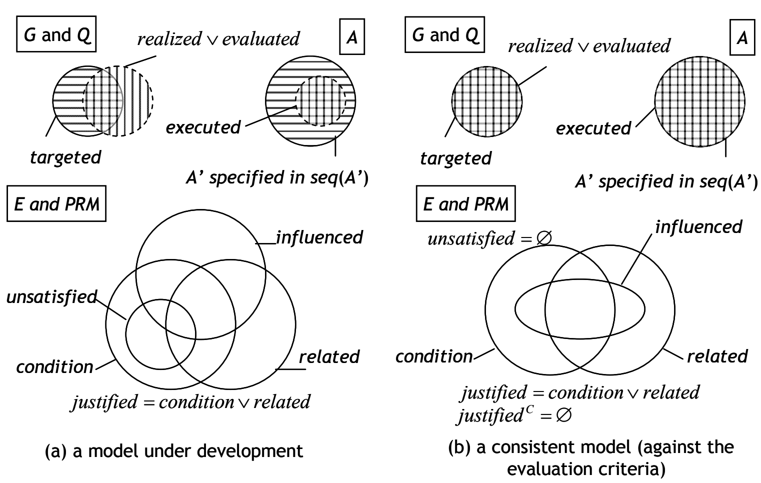

Fig. 3.8 Relations among the labeled element sets

3.3.2 Suggestion algorithm

This algorithm supports generation of new activities (services) in a PSS model to improve its performance in terms of the evaluation criteria in the previous subsection. To generate new activities to increase the performance of a new PSS model under consideration, the algorithm searches the activities that potentially increase the consistency. These activities are defined in the PSS models, which have been registered in advance (e.g., in the database of *Service CAD* introduced shortly). The suggestion algorithm is different from the evaluation algorithm in two ways. First, it needs designers to perform selections among the automatically generated options. Second, it uses the class hierarchy of model elements in order to bind the elements in a PSS model under consideration with those in the registered PSS models.

The suggestion algorithm is described in Fig. 3.9. The designer first selects one of the elements in a PSS model under consideration. The select element is usually one of the unrealized goals, unevaluated quality criteria, and unexecuted activities identified by the evaluation algorithm. The designer can also select other elements to find alternative activities. The designer then selects the type of activities to generate a template shown in Fig. 3.10. The templates are classified into direct, enhancing, and enabling services. They are used to find the bindings of “what” (the selected model element) and “how” (the selected service type) between the query of designer about the PSS model under consideration and the registered PSS models. Figure 3.10 shows examples of the templates. In Fig. 3.10, nodes with asterisk (*) indicate the selected element at the first step. Colored (gray) nodes with solid circumference indicate the elements that exist in the both template and the registered PSS models, and they are bound during the suggestion process. Colored (gray) nodes with dashed circumference indicate the elements that do not exist in the PSS model under consideration, and they are to be found from the registered PSS models.

To bind the elements in the template constructed from the query of designers about the PSS model under consideration and the elements in the registered PSS models, the class hierarchy of service elements is introduced. Two elements between the template and the registered PSS models are bound, when the classes of elements in the template are the same class or the super class of elements in registered PSS models (Fig. 3.11). The process to find bindings between a PSS model under consideration and the registered (concrete) PSS models using the class hierarchy is natural in the context of conceptual design, because a conceptual design process starts with abstract descriptions and the design process is completed with concrete descriptions.

At every comparison between the template and one of the registered PSS models, multiple bindings may be found and collected. This comparison is iteratively performed between the template and each registered PSS model. After the iteration, the designer selects one of the collected bindings in one of the registered PSS models.

To complete the suggestions, the relations of goal instances, quality instances, activity instances, and constituents in a service environment between the PSS model under consideration and the selected PSS model should be defined. Some relations have been identified during the binding process. The designer creates the rest of the relations as follows. Some elements in the selected PSS model are considered as existing elements in the PSS model under consideration. In this case, the relations defined on elements in both models are combined. For instance, a constituent in the selected PSS model is considered as one of the existing constituents in the PSS model under consideration. Its relations and parameters are then added to the respective constituent. Other elements in the selected PSS model are considered as independent elements from the existing elements. In this case they are instantiated on the PSS model under consideration. Relations between the instantiated elements and the existing elements are explicitly defined by the designer.

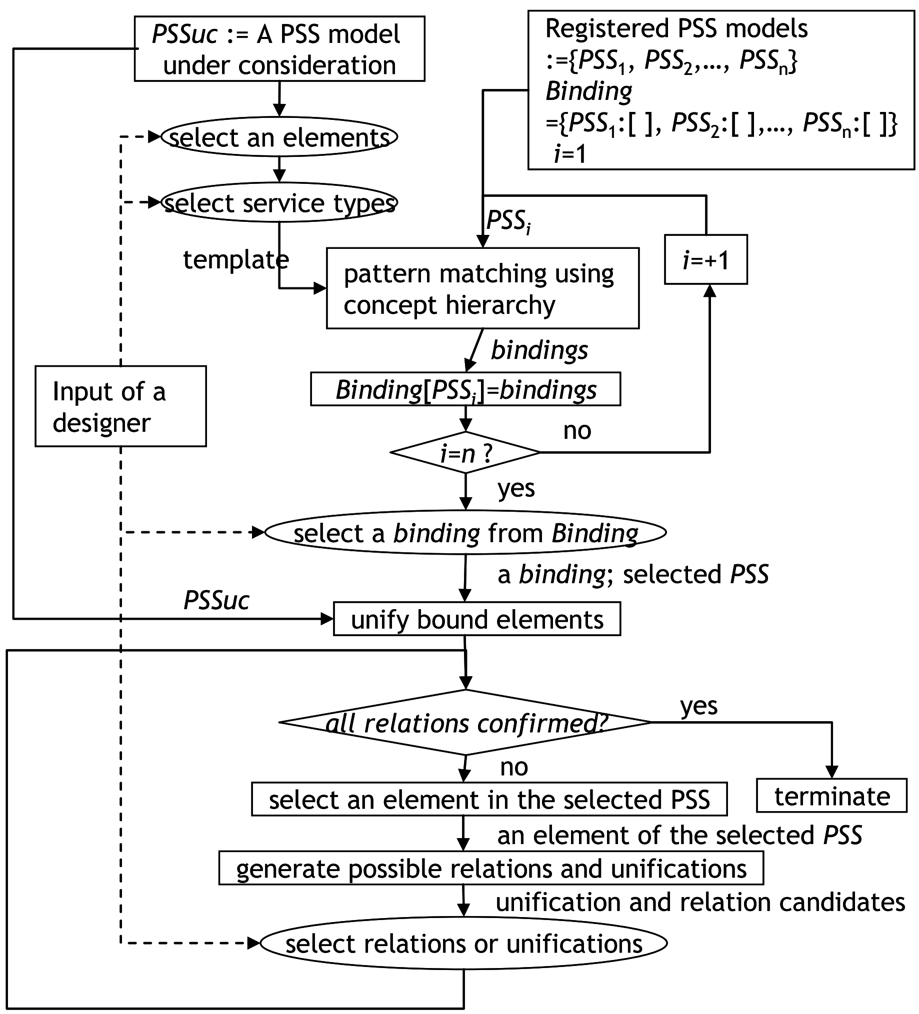

Fig. 3.9 The suggestion algorithm

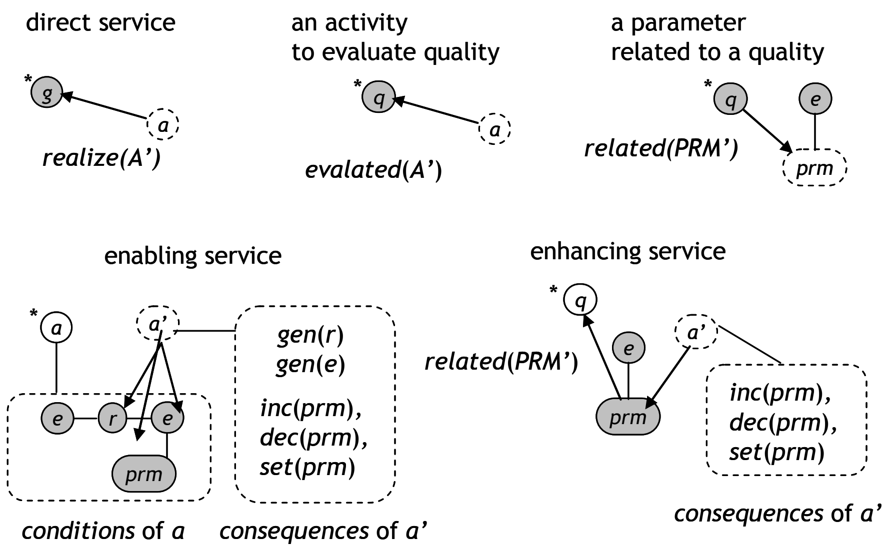

Fig. 3.10 Examples of template to evaluate the matching between two PSS models

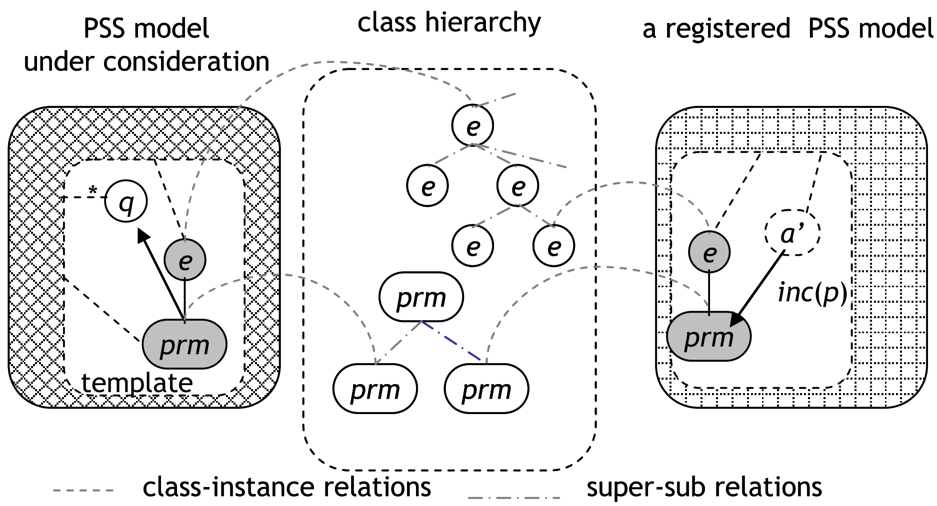

Fig. 3.11 Class hierarchy to relate elements between two PSS models in case of enhancing service

3.4 Service CAD

This subsection presents *Service CAD* as a PSS modeling tool for concept design. It employs the formal PSS model and computational design supports presented in the previous subsections. This subsection first introduces its architecture. After that the conceptual design process of PSSs using *Service CAD* is described. Finally, implementation of *Service CAD* is described.

3.4.1 Architecture of *Service CAD*

Figure 3.12 shows the architecture of *Service CAD*. *Service CAD* consists of a model builder, a model browser, a class hierarchy builder, an inference engine, a rule builder, and a rule manager. Information used during the design process is stored in a model base, a class hierarchy base, and a rule base.

The *model builder* is used to construct a PSS model. The evaluation and suggestion algorithms are applied to a PSS model on the model builder. The developed PSS model on the model builder is registered into the *model base*. The *model browser* shows one of the registered PSS models specified by the designer. The registered PSS models are instantiated on the *model builder* when necessary. The *model browser* also functions as a clip board, where the designer temporally stores a set of partial models to be used during the design process. The designer can specify the types of model elements and relations to be displayed on the *model builder* and the *model browser*.

The designer constructs the class hierarchy of service goal and quality instances, and elements in service environment (i.e., constituents, relations, and parameters) on the *class hierarchy builder*. Elements of PSS models with the above types have class-instance relations with one of the elements in the respective class hierarchy. Super-sub class relations are defined between two elements in the same class hierarchy. The developed class hierarchy is stored in the *class hierarchy base*.

The *inference engine* is one of the forward chaining engines described in Forbus and de Kleer (1993). To use the inference engine, PSS models and the class hierarchy are represented by a set of facts, while the statements in the formal PSS model presented in Section 3.2 are represented by a set of rules. Furthermore rules about quantities and class-instance relations are defined. If necessary, the designer can define a set of rules specific to PSS models on the rule builder.

The *inference engine* is triggered multiple times during an execution of the evaluation algorithm and the suggestion algorithm. At the every execution of *inference engine*, some facts and rules irrelevant to specific tasks are removed to increase the speed of reasoning. Selection of the facts and the rules are handled by the *rule manager*.

3.4.2 PSS design process using *Service CAD*

The PSS concept design process using *Service CAD* consists of initialization, development, and completion phases. The design process is shown in Fig. 3.13.

At the initialization phase, the designer defines the initial set of goals G'_0, quality criteria Q'_0, activities A_0, and environment E'_0. Furthermore a set of PSS models are developed and registered in the model base. The registered PSS models are developed by this design process in advance.

At the development phase, the designer develops a PSS model based on the initial model. The designer uses the evaluation algorithm and the suggestion algorithm for the development of a PSS model. Alternatively, the designer can manually add elements and relations to the PSS model. This development process is an iterative process.

At the completion phase, the designer finishes the development of a PSS model and registers it in the model base. A criterion to indicate the completion of model development is obtained from the results of evaluation algorithm.

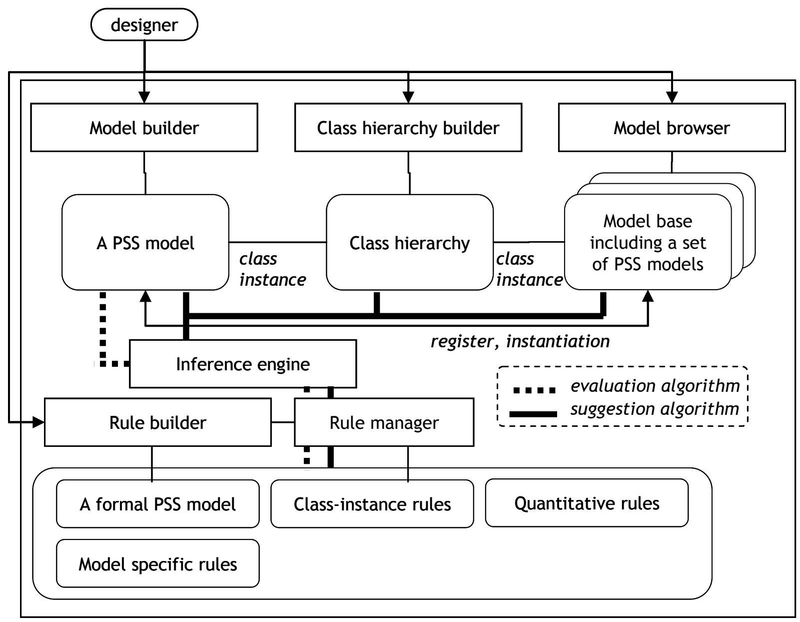

Fig. 3.12 The architecture of *Service CAD*

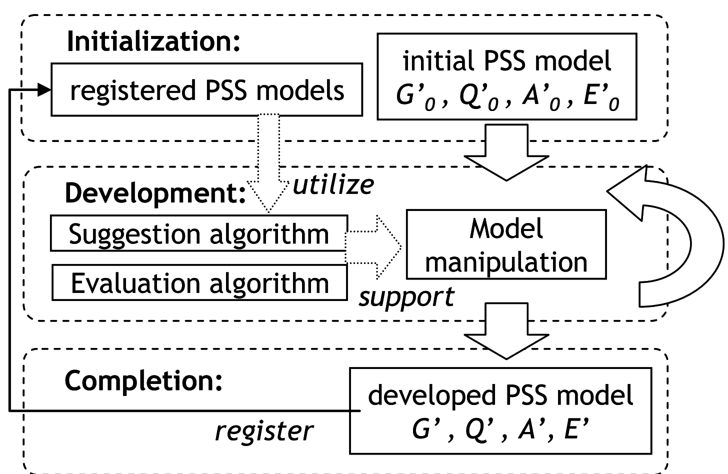

Fig. 3.13 A PSS design process using *Service CAD*

3.4.3 Implementation of *Service CAD*

Figure 3.14 shows a screen capture of *Service CAD*. It is implemented in Python, an object oriented programming language. The user interface is prepared with the pmw (Python Mega Widget) and tkinter (tk interface for Python) libraries.

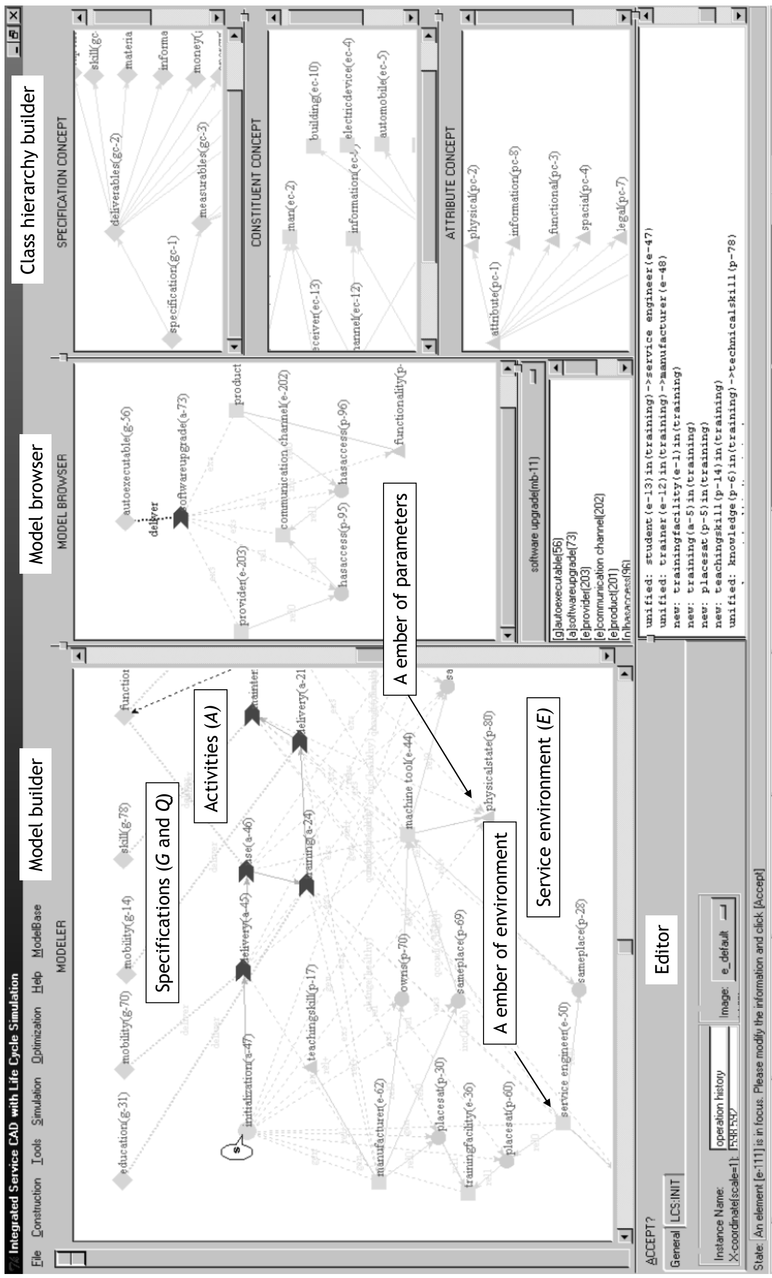

Fig. 3.14 The graphic user interface of Service CAD

3.5 Illustrative examples

3.5.1 Integrating functional upgrading services at different PSS types

In this example a PSS design process using *Service CAD* is described. During the design process, a designer systematically generates PSS design concepts described with the present formalization, while utilizing the implemented evaluation and suggestion algorithms for the systematic generation of design concepts. The concepts are designed to satisfy the different goals characterized by the types of PSSs (Tukker and Tischner 2006). Furthermore, the model performance is increased by introducing functional upgrading service of products into the designed concepts. In this case study, functional upgrading service is applied to complex computer embedded products (such as machine tools and medical diagnosis equipments, rather than consumer products) in the design concepts, because the service is suitable for these products that are reconfigured to meet the specific needs of customers through the entire life cycle, and because various service contents, channels, and providers within a PSS are necessary to do so.

Functional upgrading service in PSSs

Functional upgrading service for computer-embedded systems maintains the newness of functionality by replacing some system elements with shorter function lifetime (such as computer software, hardware and those peripherals), while continuing the utilization of other system elements with longer functional and physical lifetime (such as mechanical components).

Given that the three types of PSS classification such as product-oriented, use-oriented, and result-oriented PSSs (Tukker and Tischner, 2006), the value addition by functional upgrading service for products should be performed in corporation with the delivery of ownership, functions, and results of the utilization. As is described below, *Service CAD* systematically supports decision makings of a designer regarding such design problems by evaluating the current design concepts and suggesting alternatives to improve the design concepts.

Initialization

The designer first prepares the initial description of a PSS model and the description of PSS models registered for the suggestions. The initial description of a PSS model consists of goals, quality criteria, and members in environment (Fig. 3.15). Activities shown in Fig. 3.16 are not included in the initial description, because they will be instantiated on the PSS model using the suggestion algorithm. Class names, which are assigned to all elements in the initial description, and the relations between them, are defined in the class hierarchy. Parameters of the members of environment and their value do not have to be defined in the initial description, because they will be added with the instantiation of activities appeared in Fig. 3.15 by executing the suggestion algorithm.

Table 3.3 lists a part of activities in the registered PSS models in the case study. Although the prepared PSS models contain an activity, a PSS model in genera, can contain multiple activities. The case study assumes that the quality *newness* is related with the *functional state* of products and the relation is a monotonic function. In other words, increasing the value of functional state enhances the quality of service evaluated in terms of the newness. Since each element in PSS models has a class name defined in the class hierarchy, Table 3.3 shows the class names of the elements instead of their original instance names.

As is shown in Table 3.3, the goals to be realized by an activity do not always correspond to the specific state transition of the environment as a result of its execution. For instance, the maintenance service improves the physical states of products by delivering the *skill* of engineers, while the mechanical upgrading service gives the same effect by delivering (new) *mechanical components*. Similarly, the software upgrading service improves the newness of products by delivering *information* as executables instead of the delivery of mechanical components by the mechanical upgrading service. Furthermore, an activity, which causes the similar effects on the environment, is interpreted as service that realizes the delivery of different contents. In Table 3.3, for instance, a passenger in the service to deliver mobility (transportation1) changes his/her spatial state and he/she becomes the receiver, while goods of a receiver in the service to deliver goods (transportation2) change its spatial state and it becomes the contents for the receiver. These flexible descriptions of service do not mean that the descriptions are incomplete and that the interpretations therefore cannot be defined uniquely. Rather, service is understood and reasoned based on multiple interpretations.

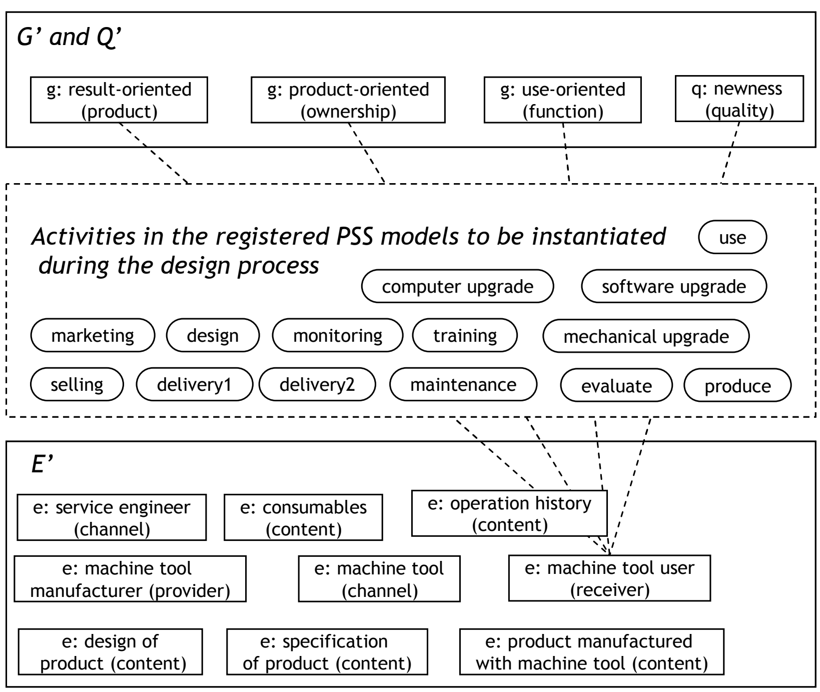

Fig. 3.15 Initial description of the PSS model

Table 3.3 Example of activity instances in the registered PSS models

Activity *a*	**Description of conditions *cond*(*a*) and consequences *cons*(*a*)**
selling	*cond*(selling) = [provider, receiver, goods, own(provider, goods)] *cons*(selling) = [gen(own(receiver, goods)), del(own(provider, goods)), specifies(ownership) = receiver, realize(selling) = ownership]
transportation1	*cond*(transporation1) = [provider, receiver, goods] *cons*(transportation1) = [gen(spatialState(receiver, goods)), set(place(goods), receiver), specifies(goods) = receiver, realize(transportation1) = goods]
transportation2	*cond*(transporation2) = [provider, channel, destination] *cons*(transportation2) = [gen(spatialState(passenger, destination)), set(place(passenger), destination), specifies(mobility) = receiver, realize(transporation2) = mobility]
maintenance	*cond*(maintenance) = [user, engineer, product, skill(engineer) = high, spatialState(engineer, product)] *cons*(maintenance) = [inc(physicalState(product), healthy), specifies(skill) = user, realize(maintenance) = skill]
mechanicalUpgrade	*cond*(mechanicalUpgrade) = [engineer, product, newParts, skill(engineer) = high, spatialState(engineer, product)] cons(mechanicalUpgrade) = [inc(physicalState(product), healthy), inc(functionalState(product), updated), realize(mechanicalUpgrade) = newParts]
softwareUpgrade	*cond*(softwareUpgrade) = [server, channel, product, executables, informationConnection(server, channel), informationConnection(product, channel)] *cons*(softwareUpgrade) = [inc(functionalState(product), updated), realize(softwareUpgrade) = information]
use	*cond*(use) = [user, product, consumables, spacialAccess(user, product), physicalState(product)=healthy)] *cons*(use) = [dec(physicalState(product), malfunction), del(consumables), realize(use) = function, specifies(function) = user]
produce	*cond*(produce) = [producer, production facility, product design] *cons*(produce) = [gen(product), gen(own(producer, product)), set(place(product), producer)]
evaluate	*cond*(evaluate) = [user, product, spatialAccess(user, product)] *cons*(evaluate) = [specifies(newness) = user, eval(evaluate) = newness, newness = monotonicallyIncreasingFunction(functionalState(product)]

Development

The designer develops both a sequence of activities to realize the goals and specify environment to meet the execution conditions of the developed sequence of activities. To do so, the designer manually modifies the description of the PSS model and employs the evaluation and suggestion algorithms. Using the evaluation algorithm, the designer identifies the unrealized goals, unevaluated and unenhanced quality, and (un)necessary elements in the service environment. After the identification, the suggestion algorithm is employed to search for activities instances to improve the PSS model in terms of the evaluation criteria.

Figure 3.16 describes how activities in the registered PSS models are inferred from the PSS model starting from the initial description. First of all, activities to realize the delivery of contents specified by each PSS types are instantiated (realize). *Selling*, *use*, and *product delivery* activities deliver the ownership of the machine tool, the function of the machine tool, and the product manufactured with the machine tool, respectively. These activities are chosen by the designer among other alternative activities. For instance, *production* (by the customer) is an alternative activity of product delivery from the machine tool manufacturer to the customer for the result-oriented PSS.

In terms of the quality *newness*, the designer first generates activities that evaluate the quality, and finds the related parameters in the environment. After that, the designer finds activities that enhance the quality through the related parameters. In this case study, the model base includes an activity *evaluate* for the evaluation of the *newness* of a *product*, *mechanical upgrade*, *computer upgrade*, and *software upgrade* activities to increase the *functional state* of a product in the registered PSS models. Especially these upgrading activities are different in terms of their execution conditions and consequences of the execution.

To enable activities to realize the goals, evaluate the quality, and enhance the quality, other activities are necessary to cause the state transitions of the environment. For example, the delivery of a machine tool is necessary for the customer to use the machine tool. Furthermore, to enable the continuous use of the machine tool, consumables should be delivered to the customer and the physical state of machine tools to be recovered. The process to generate the enabling activities for all the instantiated activities is performed iteratively until the conditions of the generated activities are satisfied by the initial state of the environment.

In parallel with the development of activities, the descriptions of existing constituents, relations, and parameters are specified, and new elements are introduced to the environment. For instance, the machine tool does not have any parameters when *selling* is instantiated to deliver the ownership of a machine tool. It obtains its physical and functional parameters when *use* and *evaluate* activities are introduced, respectively.

The newly instantiated activities and elements in the environment from the registered PSS models are unified with existing elements in the PSS model during the execution of the suggestion algorithm. The possibility of unification between two activities is evaluated by comparing the delivered service contents and execution conditions in new activities with those in the existing activities. For instance, *computer upgrade* is unified with *consumable delivery*, because both activities deliver *products*. *Mechanical upgrade* is unified with *maintenance*, because both activities require the *skill* of engineers. Furthermore, *new parts* in mechanical upgrade are delivered together with the *service engineer* at the delivery of engineer. *Software upgrade* is executed with *monitoring*, because both activities deal with the delivery of *information* contents (operation history and executables).

Completion

The designer completes conceptual design of a PSS when the evaluation algorithm does not find unrealized goals, unevaluated quality, unexecutable activities, and unnecessary elements in the environment. Figures 3.17, 3.18 and 3.19 show examples of the completed PSS design concepts based on the product-, result-, and use-oriented PSS types. Figures 3.17 and 3.18 become incomplete when the concepts are evaluated in terms of newness of products, because they do not have activities to evaluate the quality.

In case of the product-oriented PSS design concept, delivery of ownership by selling activity is the sufficient condition to complete the design. In order to relate the design concept with functional upgrading service (and other activities), the designer needs to explicitly define use of machine tool after the delivery of the ownership. After that, the design process will follow the process based on the use-oriented PSS type described shortly.

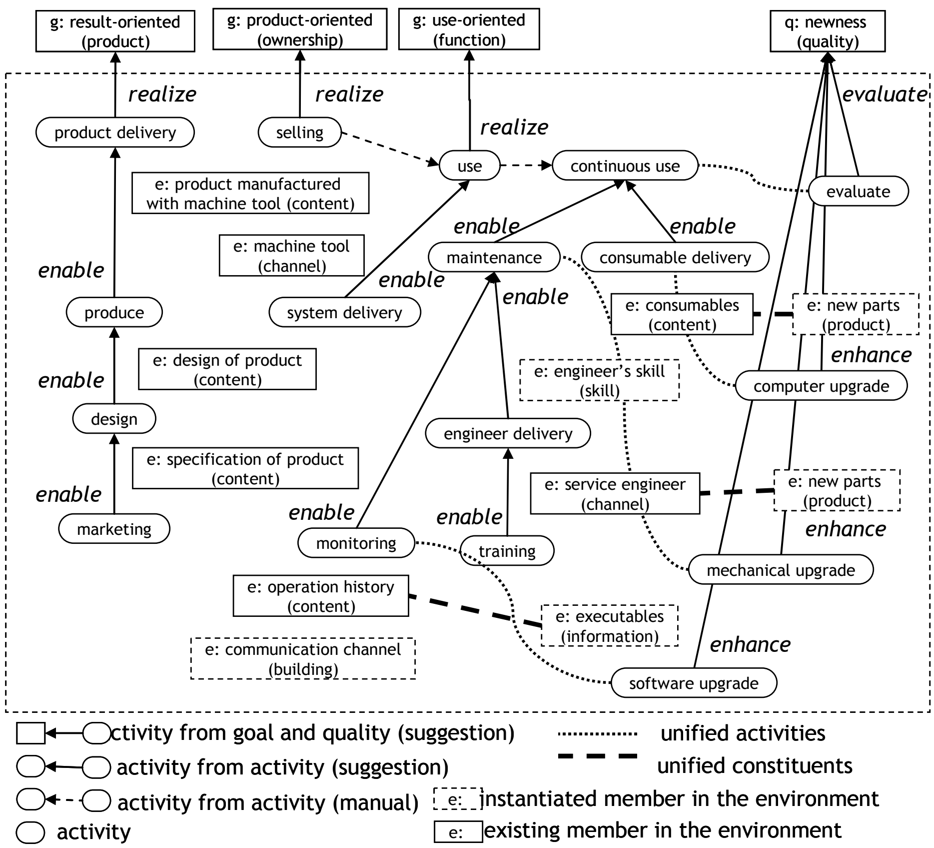

Fig. 3.16 Flows of generation of activities during the design process

In case of the use-oriented PSS design concept, physical and functional state of the machine tool, and technical skills of service engineer become the parameter of the constituents of service environment. Maintenance, upgrading, and training activities construct a PSS that satisfy the delivery of the function, while enhancing the quality of the design concept in terms of newness. As is described, various combinations exist in unifying activities and members of the environment, and the alternatives are generated by executing the suggestion algorithm.

In case of the result-oriented PSS design concept, the parameters of the machine tool and the service engineer become irrelevant, because the customer does not have chances to directly use the machine tool and evaluate its performance. The design concept rather focuses on the relations between the machine tool manufacturer and the customer in terms of the delivery of information contents to produce the products manufactured by the machine tool (specification and design of manufactured products).

Thorough the comparison of the design concepts with respect to different PSS types, the designer can identify necessary design information in the model description. Following the instantiation of activity instances triggered by the respective service goals, different parameters and relations of the elements of the environment are incrementally identified.

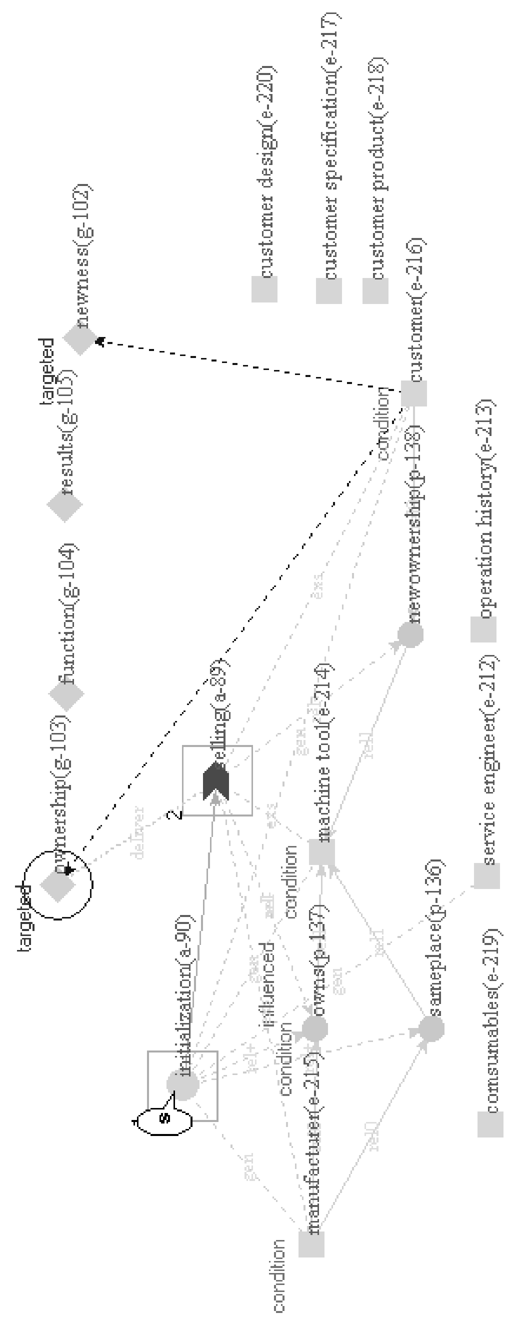

Fig. 3.17 Description of a product-oriented PSS (by introducing a selling activity)

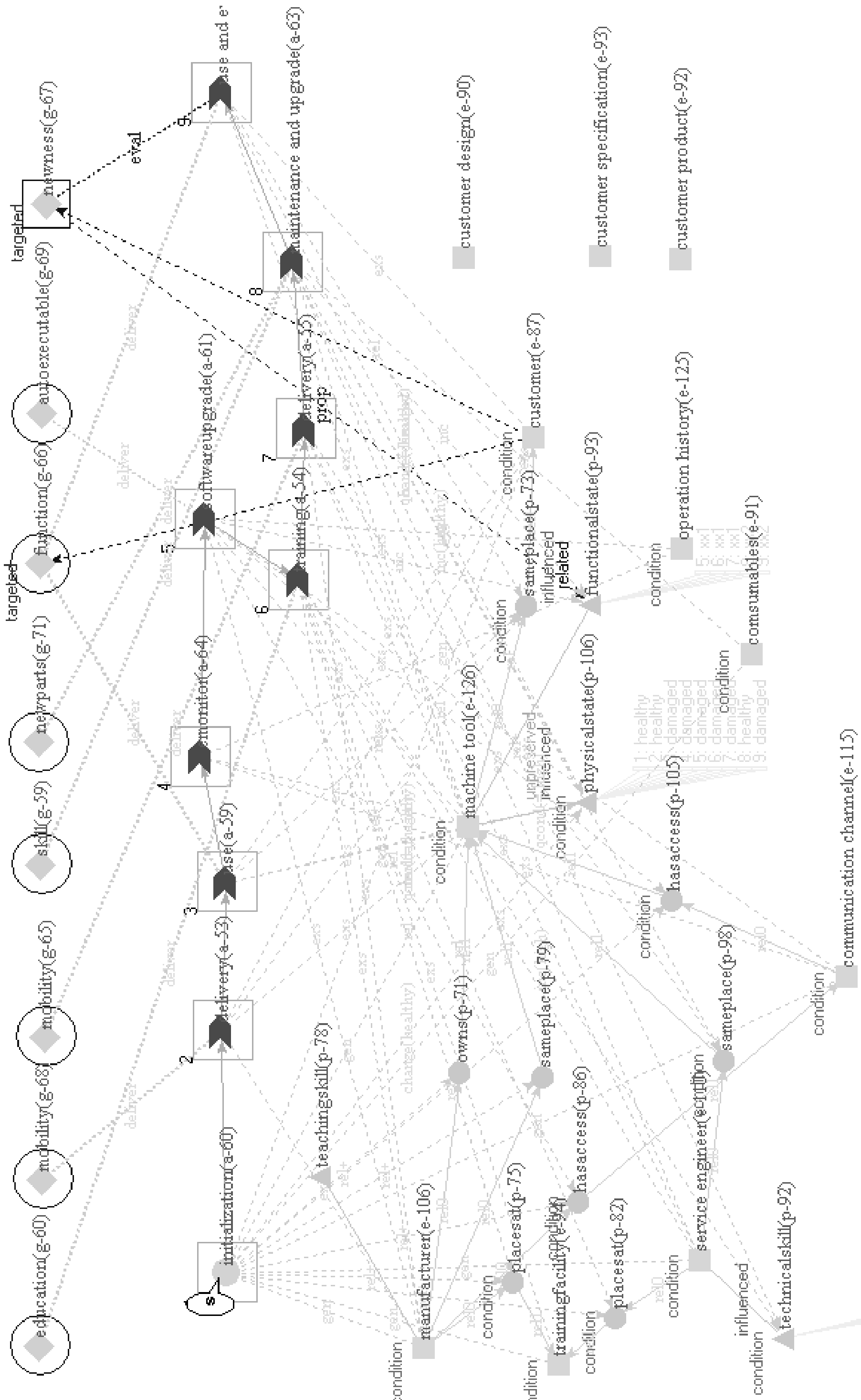

Fig. 3.18 Description of a use-oriented PSS

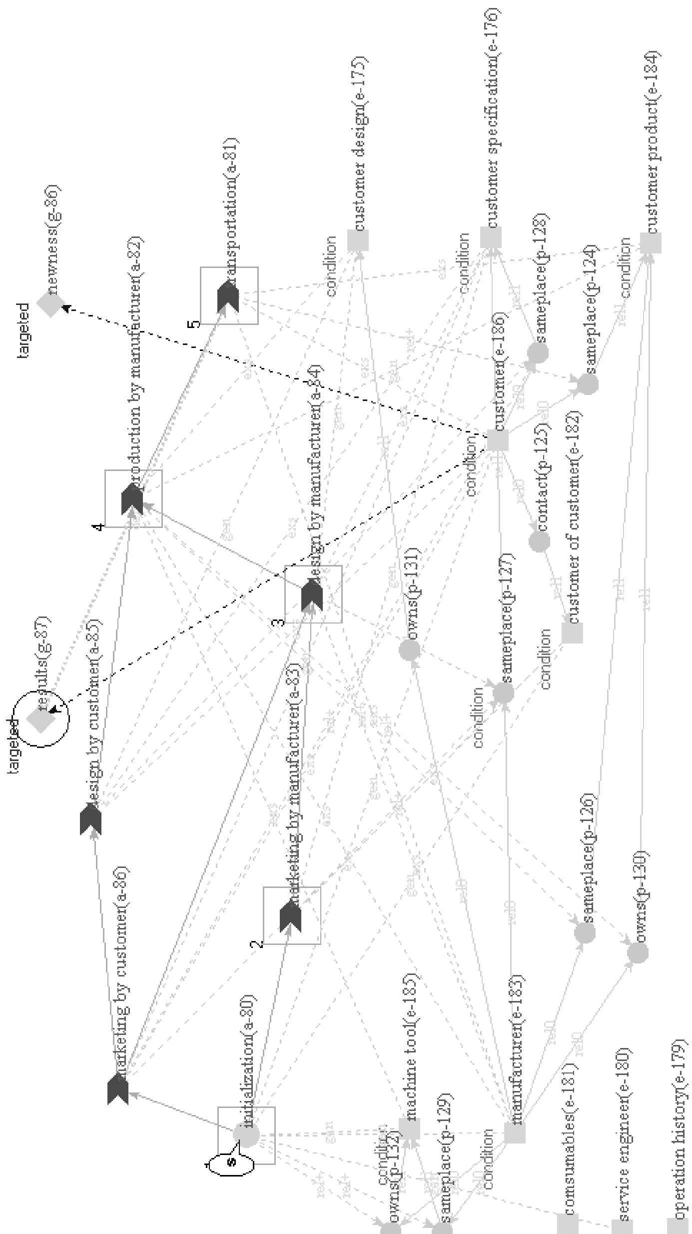

Fig. 3.19 Description of a result-oriented PSS

3.5.2 Relating service providers and receivers in the health care industry

In this example, products and services offered by manufacturers of medical instruments (e.g., magnetic resonance imaging (MRI) scanners, image processing tools) are collected as the core elements of a PSS design concept. The reason is that existing services by the manufacturers have been diverse in terms of ownership structure, service contracts, and machine selections according to the needs of machine owners, doctors, and patients (Scott and Atlas 2004; Sistrom and McKey 2005; Levin et al. 2008).

Information collection and organization

Integrated product-service offerings of several medical instrument manufacturers were collected based on the documentation available in public domain (e.g., homepage, product catalogues, and information about service contracts). Services by manufacturers, activities of other stakeholders, and automated operations of medical instruments were retrieved from the documentation. After that, the elements in the collected descriptions were classified into the formalization as described in Section 3.2. Finally, conditions and consequences of these activities, and related services goals and quality criteria were also defined to form a PSS model used for the suggestion algorithm. Some of the PSS models are shown in Fig. 3.20.

The above collection and classification steps were subjective, for no collection guidelines compatible with the formalization and no programs to automatically perform these steps were available. However, subjectivity of the collection step does not influence the analysis at the information utilization at the concept generation step.

Utility of the stored primitives in generating PSS design concepts is analyzed by adding new products and services on a base design concept using the suggestion algorithm. The base design concept was built on the model builder. Figure 3.21 shows the base design concept on the screenshot of *Service CAD*. The concept included a simple workflow in a health care service, starting from the preparation of a medical instrument to the consultation by a doctor about the health state of a patient. Note that the concept did not include the manufacturer of a medical instrument.

Generating PSS design concept

Figure 3.22 shows how a designer introduces a manufacturer as a provider in the base design concept and how relations between the manufacturer and the patient shown in both Figs. 3.21 and 3.22 were systematically defined using the suggestion algorithm. (Alphabetical symbols in Figs. 3.12 and 3.22 correspond to those in the following paragraphs.)

First, the designer added “comfort (a)” as a quality criterion evaluated by the patient (b). Two PSS models “comfortByLighting” and “comfortByProductDesign” in Fig. 3.20 were suggested by Service CAD, because these models included an activity to change the brightness of a room, or the size of a product, and these parameters were also related with the comfort of the respective receiver in these PSS models (see Fig. 3.20). After instantiating these PSS models on the base model, the designer defined the room (c) as a new channel, and the product as the instrument (d) in the base concept, respectively. In consequence, size (e) is introduced as a parameter of the instrument. After that a PSS model "designAndProduction" in Fig. 3.20 was suggested, because the manufacturer of the lighting device (f) was not defined in the base concept. The designer defined it as the manufacturer of the instrument (i.e. manufacturer (g)). Introduction of "convenience (h)" as a quality criterion evaluated by the operator (i) becomes a trigger of introducing a a PSS model "convenienceByProductDesign" in Fig. 3.20.

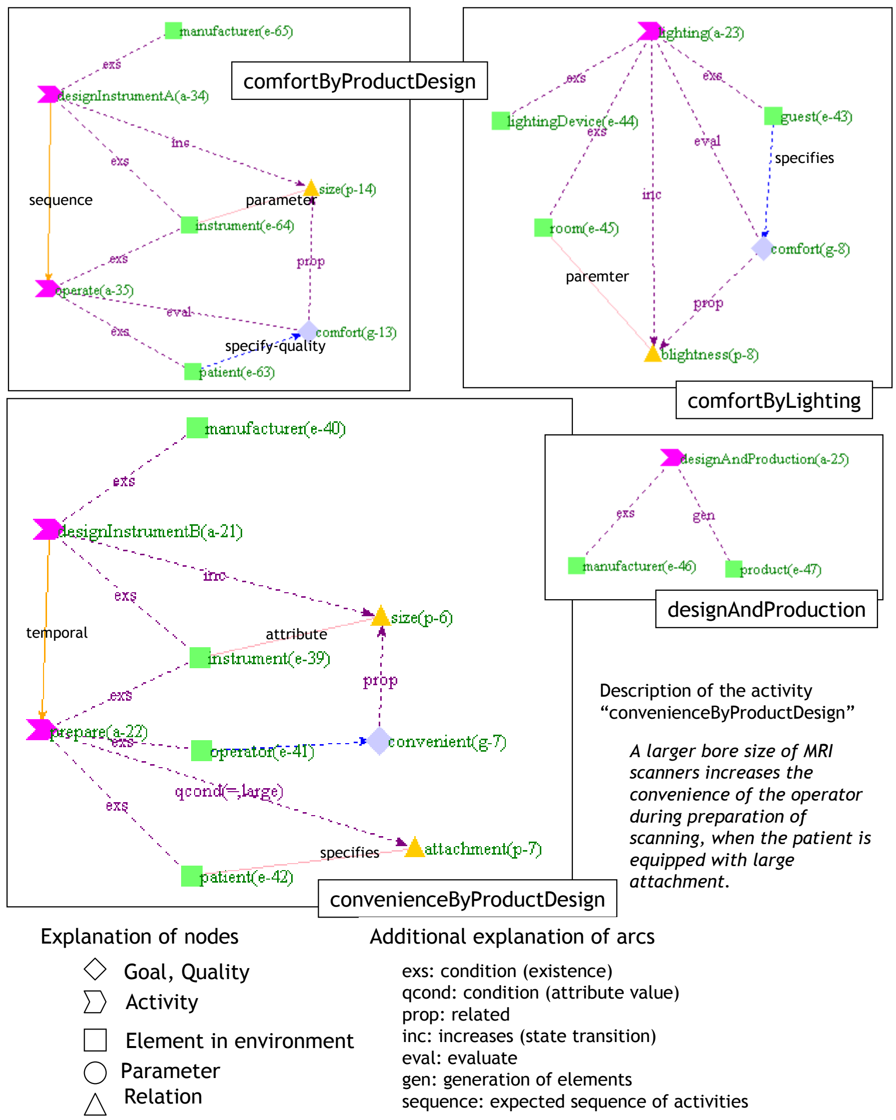

Fig. 3.20 Examples of PSS models stored in *Service CAD*

As a result of adding these PSS models to the base design concept, multiple roles of the instrument manufacturer to increase the quality specified in the concept were clarified. Furthermore, the parameters of products corresponded to the added activities (e.g., brightness of the operation room (j)) were specified.

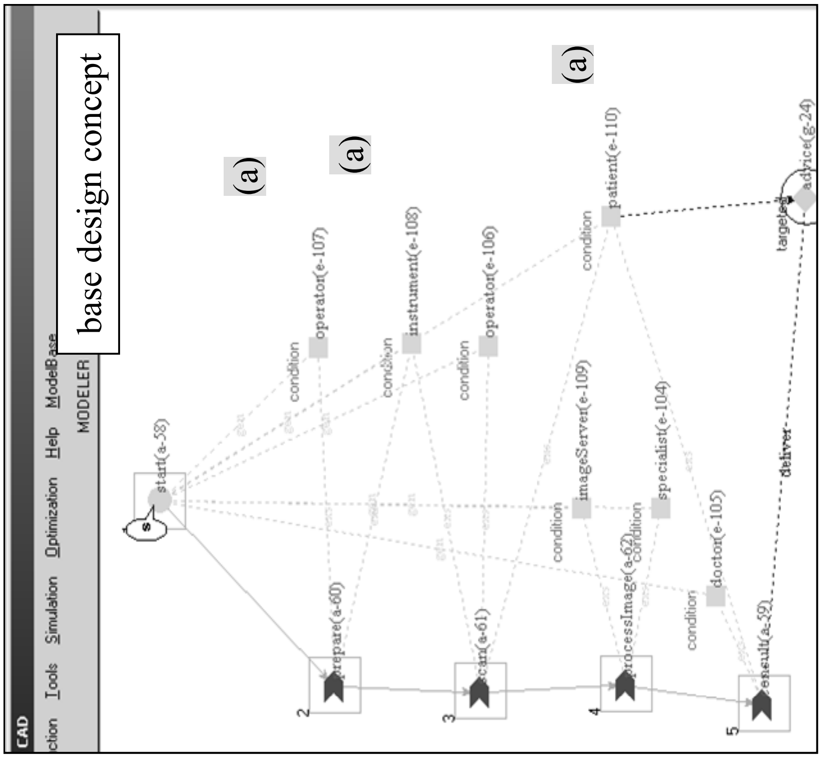

Fig. 3.21 The base design concept developed on *Service CAD*

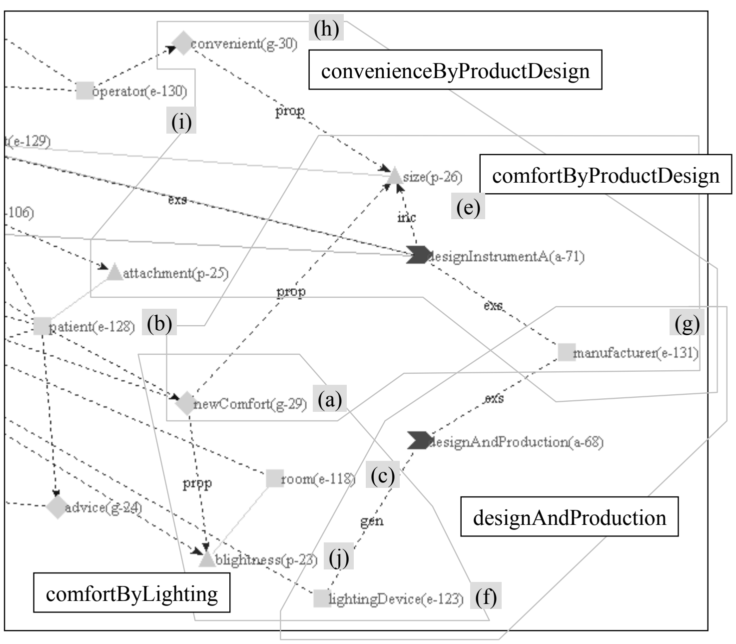

Fig. 3.22 Extension of a PSS design concept with suggestions

3.6 Discussions

This section describes the characteristics and limitations of functions of *Service CAD* based on the proposed PSS formalization. These descriptions are related with future research issues regarding the improvement of service CAD tools for PSS concept design.

Extension of quality evaluation

Service CAD is equipped with facilities to evaluate the value of quality based on the value of parameters of constituents in a service environment. Qualitative descriptions of the evaluation functions are used to indicate the direction of the parameter modification to enhance the quality. In this way, the suggestion algorithm can utilize the qualitative function descriptions to search for potential activities to enhance the quality.

However, the descriptions in *Service CAD* are limited to monotonically increasing and decreasing functions. Capability of service CAD tools in describing complex relations between the values of quality instances and those of the parameters can be useful. For instance, complex relations can be found among the usability and cost of a machine tool for an operator as quality and the size of the machine as a parameter, where middle size machine tools give the maximum usability and smaller ones give better cost effectiveness. In order to implement such relations in *Service CAD*, the usability is related with the gap between the optimal size and the actual size. As a result, the original relation between the usability and the size is lost.

Moreover, *Service CAD* cannot compare the values of two different quality instances or parameters. In this example, the size of the machine tool should be determined with the consideration of both the usability and the cost effectiveness. One way to describe the comparison is to introduce relations among the values such as correspondences (Forbus 1984). Otherwise the values construct individual performance criteria to represent the trade-off performances of a PSS model.

Comparative analysis of modeling and reasoning techniques among functional (product) design, service design, and PSS design

Service CAD has been developed so as to provide similar supports performed by (product) CAD tools for conceptual (functional) design (Chapter 1.1.3). As is presented at the introduction of this chapter, the tools are based on the work in function modeling and function reasoning. The work focuses on the representations of functions and related concepts in an abstract level, and algorithms to support conceptual design of products using these representations. As Far and Eramy (2005) classified the design problems, which function modeling and reasoning techniques can support to solve, the proposed evaluation and suggestion algorithms support the similar problem solving tasks in conceptual design of PSSs as follows:

- identification of the performance of A' and E' a PSS model in terms of the evaluation criteria (used in the evaluation algorithm);
- explanation of necessity of activity *A* and members of environment *E* such as channels and providers regarding their contributions to the performance;
- selection of an activity *a* and a proper set of providers, channels, and contents from all the members of environment *E* in order to increase the performance; and
- verification of whether an activity *a* under the given environment *E* increases its performance.

The series of research to combine function reasoning and qualitative simulation are referred to as model based reasoning (MBR) (Umeda and Tomiyama 1997). In MBR, qualitative simulation is used to evaluate the behavior of products and function reasoning is to connect the simulated behavior and function representation. One of the methods called Qualitative Process Theory (QPT) uses a process based representation (Forbus 1984). The behavior in QPT is instantiated by the occurrences of processes. However, processes in QPT are different from activities in service and PSS modeling methods. It is because of that activity instances and the orders of activity instances are explicitly defined by the designer, while occurrences of processes and those causal relations are solely determined by initial conditions of structure and given sets of physical laws. Furthermore, the activity instances are treated as instantaneous events that cause discrete state transitions, while the processes in QPT cause continuous state transitions under a certain time interval.

In spite of the differences between the activity and the process in terms of the representations and the reasoning principles, the research for the development of service CAD tools for conceptual design of PSS can obtain considerable amount of lessons from that of model based reasoning.

Representing PSS design concepts

At the second example, a generation process of PSS design concept was presented instead of presenting the entire concept. One of the reasons is that a concept in general consists of a number of elements and relations, and displaying the entire information does not help designers understand the concept and communicate with other designers. To improve the interpretability of a PSS design concept by designers, separate views can be used, as suggested in use of Service Explorer (Hara et al. 2008). As is demonstrated in this section, the description regarding such decisions in the design process as selection and instantiation of primitives, addition of relations between the elements in primitives and the base concept, can be another source to help the designers understand a PSS design concept.

Introduction of different views

The presented formal PSS model is relatively complex compared with other service modeling and PSS modeling methods presented in Section 2.2. It is because of that the presented model includes the representations of those methods, which are necessary for the conceptual design of PSSs. Therefore, the presented model can be used as the meta-level representation, while the designer can construct a PSS model with different views (aspects) such as process-oriented (*e.g.*, service blueprint), stakeholder-oriented (*e.g.*, system map), or correspondence-oriented (*e.g.*, Serviset) representations.

Relating service providers and service receivers

As shown in Fig. 3.20, few relations between quality criteria specified by patients with products and services offered by instrument manufacturers were found, while many relations between the offerings and quality criteria specified by the instrument users were found. This fact suggests that the collected documentation does not include relations between the instrument manufacturers and patients. For instance, patients normally do not know the manufacturer of medical instruments and they do not give preferences to a medical care service in terms of the service of the manufacturer.

Separating concept generation from information organization

In the second example, the information organization step to develop PSS models stored in *Service CAD* was separated from the information utilization step to generate PSS design concepts using the stored PSS models. These steps can be performed by a team of experts and PSS designers. The experts in specific product and service domains are engaged in information collection and organization, while PSS designers systematically generate concept by effectively using the information.

Differentiating service contracts in a product life cycle

The instrument manufacturers observed in this section offer diverse contracts with instrument users in the life cycle of instruments. These contracts include such service types as scheduled maintenance, parts supply, remote diagnosis, and online consultation by service engineers. Comparison of these contracts among the manufacturers has shown similarity of the offered service types and differences in terms of configurations of service types within a service package. Furthermore, some service types such as workflow optimization require the information specific to individual instrument users for the service execution, and remote diagnosis service is an enabling service of such service types. Complexity of relation among services included a service contract suggests that differentiation of service contracts of a manufacturer from other competitors is done by configuration of appropriate service elements in a service contract in addition to design of elements in a contract.

Integration with quantitative and stochastic evaluation methods

In order to evaluate the systemic performance of a PSS, the design should be analyzed with consideration of quantitative and stochastic properties. For instance, the evaluations of customers have subjective distributions, while the parameters of constituents in a service environment may show objective but stochastic distributions (*e.g.*, probability of the deterioration of products described with bath-tub curves). *Service CAD* enables the designer to describe quantitative value changes using numerical descriptions. Although it can describe branches within the order of occurrence of activities, *Service CAD* does not relate the results of evaluations of multiple sequences of activities, which are partially overlapped.

As observed in the current implementation of *Service CAD* (Section 3.4), the authors consider that *Service CAD* and life cycle simulation (LCS) reviewed in Section 2.1.2 have a complementary relationship at the design process of PSSs. It is because of that *Service CAD* supports systematic generation of PSS models, which possess different sets of activities and constituents, while LCS instantiates a number of constituents, which have individual finite states, and evaluates the quantitative performance of a PSS model based on the number of executions of the defined set of activities, and the resulting statistical distributions of the states of the constituents. The integration of *Service CAD* and a life cycle simulator will be described in Chapter 4.

3.7 Conclusions

In this chapter, *Service CAD* for conceptual design of PSSs has been presented. Following the review of service modeling methods in Chapter 2, a formal representation of PSS and algorithms to support the conceptual design have been presented. Examples have shown the usefulness of a formal representation and the algorithms for the systematic generation of PSS design concepts. *Service CAD* has shown that its supports at the conceptual PSS design are similar to those provided by CAD tools for conceptual (functional) design, although the supporting mechanisms are different due to the differences in terms of the representation of design information. This chapter is concluded by presenting some remarks related to the research questions.

Remarks related to the research question 1b

Design information used in *Service CAD* is formalized according to the proposed PSS model. As shown by the examples, it was found that the proposed formalization allowed *Service CAD* to translate such conceptual information as PSS types (product-, use-, and result-oriented) into explicit design information used in PSS design process (goal instances to be delivered by a PSS) However, it was also found that *Service CAD* could not help describe a PSS design concept based on shared services due to the limitation of the proposed PSS model to formalize relations among multiple constituents in service environment. This limitation will be further investigated in the following chapter.

It was found that the types of design information critical to describe a PSS design concept were dependent on the design information used in generating the PSS design concept. As shown in the examples, explicit definition of product attributes in context of result-oriented PSS type was not specified, because customers were not interested in function of the product associated with the product attributes. This finding indicates that manufacturers should be aware of the roles of products as service channels in context of product- and use-oriented PSSs. It is because this PSS types allow manufacturers to introduce enabling and enhancing services that change the attribute values of products. This suggestion is consistent with the report about current PSSs in the automobile industry (Williams 2007). It is further suggested that design information to relate quality perceived by customers and product attributes should be visible from the perspective of both customers and manufacturers, in order to design enhancing service effectively.

Remarks related to the research question 2a

Service CAD could support reuse of PSS design information by organizing and storing the information as a set of PSS model used as primitives to constitute new PSS design concepts. Furthermore *Service CAD* could support concept generation process by effectively searching the stored PSS models to complement lack of elements in the design concept under construction, and support unification of these models with the design concept.

Service CAD could separate automated design tasks and manual design tasks. Example of automated tasks is search of PSS models stored in the tool. Manual design tasks include the selection of a stored PSS model to be added to a design concept, and the unification of elements in a selected PSS model with elements in the service environment of a design concept.

The performance of automated design tasks is also influenced by construction of the database of *Service CAD*. For the construction, PSS designers manually classify the design information into the proposed formalization, and define the classified information element in the concept hierarchy (class - subclass relations). It was found that automation of the classification task is difficult, because an element of PSSs can have different meanings in different design concepts (a person as a service receiver, or as a service channel) and they are differently related with other elements in the concept hierarchy defined by designers. Further research is therefore necessary to develop a method to support the classification of PSS design information and the development of concept hierarchy.

The method to organize design information into a set of PSS models in *Service CAD* is different from that in function CAD tools (Section 1.1.3), which do not initially provide sufficient information to relate function (design specification) and structure (design object). It is because of that one of the tasks of a PSS designer is to relate products and services, whose individual specification-object relations have been given.

Remarks related to the research question 2b

A change in utilizing design information results in a change in collecting and organizing the design information. Using *Service CAD*, information about products and services can be collected by experts at specific product and service domains, while the collected information is used by PSS designers. Furthermore, utilization of the design information results in the creation of design information, which relates individual products and services for specific goals and quality criteria in a PSS design concept. It was found that such information was implicit in the description of individual products and services. Therefore, further investigation is necessary to identify such information to provide answers to the research question 1b.

4 *ISCL*: Integrating *Service CAD* with a life cycle simulator

In the previous chapter, *Service CAD* has been developed as a PSS modeling tool to support PSS concept design. It has shown that information about products and services has to be formalized in order to effectively utilize computational supports for systematic PSS design. However, it has shown that the proposed formalization has limitation in dealing with quantitative information, and that *Service CAD* has therefore limitation in evaluating quantitative performances of generated PSS design concepts. In this chapter, integration of *Service CAD* and a life cycle simulator is proposed. In this chapter, mechanism and implementation of life cycle simulation employed in this study, and integration of *Service CAD* with life cycle simulation are described. It was found that the integrated tool, *ISCL* has functions to support quantitative and probabilistic PSS design using life cycle simulation. It was also found that the mechanism of life cycle simulation should be redesigned so as to deal with quantitative and probabilistic descriptions defined on *Service CAD*. This chapter is concluded with remarks on the integration in terms of organization and utilization of design information for systematic PSS design.

4.1 Introduction

In this chapter, integration of a service CAD with a life cycle simulator is proposed for the systematic PSS design. A service CAD tool is proposed as a systematic PSS modeling tool (Tomiyama and Meijer 2003). A life cycle simulator supports performance analysis of a product life cycle from economic and environmental perspectives based on life cycle simulation (Shu et al. 1996; Umeda et al. 2000). Integration of two tools requires a generic PSS model, with which designers can perform various tasks using facilities provided by them. The integrated tool, or *ISCL*, is comparable to computer aided design and engineering (CAD/CAE) tools for product design, in which designers define product models with a geometric modeler and analyze the performances with computational methods such as Finite Element Methods (Table. 4.1).

Table 4.1 Integration of a service CAD tool and a life cycle simulator

	product CAD/CAE	ISCL
Object	Product	PSS
Definition	Geometric CAD	Service CAD
Evaluation	Finite Element Method	LCS
Modeling	Geometric modeling	PSS modeling

In the previous chapter *Service CAD* has been introduced as a tool to support conceptual PSS design. The tool supports PSS modeling based on the service formalization (Tomiyama et al. 2004). It also supports designers to systematically develop alternative PSS design concepts by utilizing its evaluation and suggestion algorithms (Section 3.3). However, it cannot support evaluation of the developed design concepts from a life cycle perspective. It is partly because the design concepts do not include quantitative and probabilistic descriptions, which determine the economic and environmental feasibility from a life cycle perspective. The descriptions include, for instance, the number of products in a market, stochastic behavior of products (e.g. physical deterioration), and uncertainty in user behaviors in the life cycle (e.g. selection of available services). Precise evaluation of the feasibility is difficult at an early design phase, where sufficient information has not been collected or determined. It is nevertheless beneficial to identify potential risks of each design concept at this phase taking into account a certain range of uncertainty.

A life cycle simulator can compensate the limitation of *Service CAD* in quantitative and probabilistic PSS design, because life cycle simulation (LCS) is a quantitative and probabilistic method for product life cycle design (Section 2.1.2). LCS can be compared with other potential methods for product life cycle design. First LCS is different from life cycle assessment (LCA) and life cycle costing (LCC), which deal with the sub processes as individual elements in a product life cycle (Section 2.1.3). Second LCS is different from operations research and mathematic programming methods (Section 2.1.4), which cannot explicitly treat physical, structural and functional properties of products, which influence the performances of the life cycle.

The integrated tool, or *ISCL*, supports a designer in modeling and analysis of PSSs as illustrated in Fig. 4.1. A designer first defines a PSS model (i.e., a design concept) using the facilities provided by *Service CAD*. Second, quantitative and probabilistic descriptions are defined on the PSS model. Finally, its performances are analyzed with life cycle simulation from a life cycle perspective, and the PSS model is iteratively modified during the design process until the designer satisfies its performances.

4.2 Representing quantitative and probabilistic design information

This chapter is organized as follows. In Section 4.1, the aim of integrating a life cycle simulator with a service CAD tool in PSS design has been described. In Section 4.2, extension of *Service CAD* presented in the previous chapter regarding quantitative and probabilistic PSS design is investigated. In Section 4.3, the mechanism of a life cycle simulator integrated with *Service CAD* is described. In Section 4.4, *ISCL*, integrated service CAD with the life cycle simulator is proposed. In Section 4.5, this chapter is summarized and concluded.

Service CAD does support evaluation of a PSS model from a life cycle perspective. This incapability is derived from the specifications of *Service CAD* in restricting design information including quantity and probability as follows.

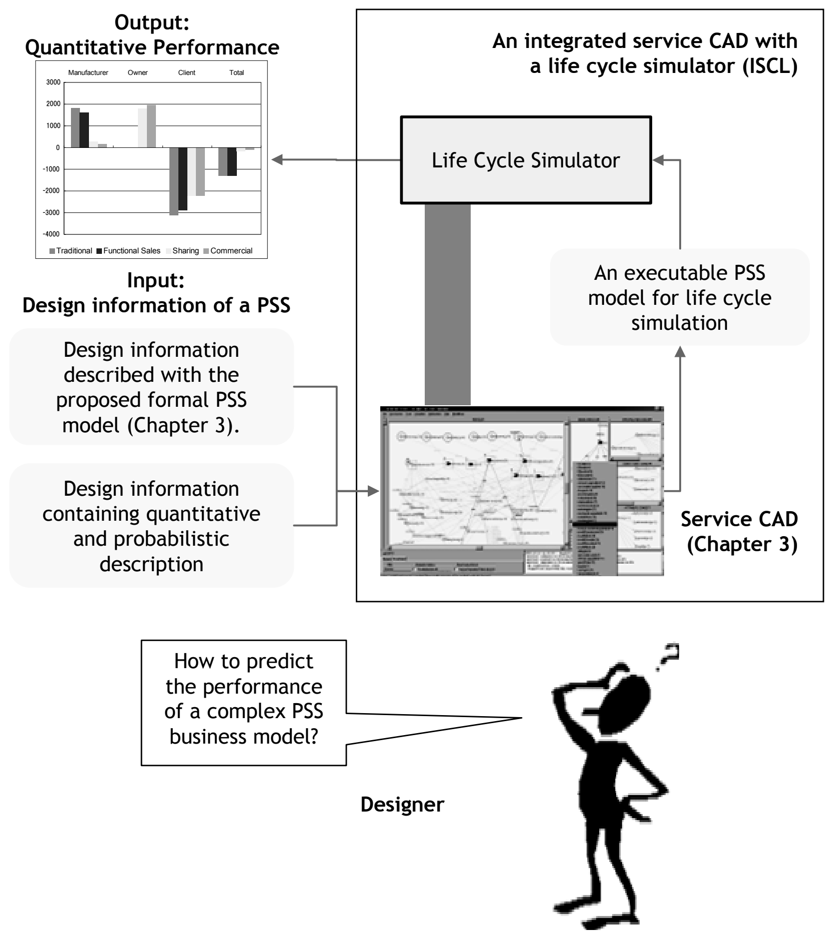

Fig. 4.1 PSS design using *ISCL*.

- Quantity descriptions in a PSS model are the parameter values of constituents, the number of constituents (e.g., products and users) in a market. They are observed at the conditions and consequences of executing activities. The parameter values and the number of constituents dynamically change as a result of executing activities. Conditions of activities do not only include quantitative descriptions of the parameter values and the number of constituents but also quantitative description of time (e.g. explicit timing of executing activities). Furthermore, introduction of the number of constituents creates additional qualitative and quantitative descriptions. They are for instance, a qualitative variety of descriptions between constituents (one car for one user, one car for many users, and many cars for many users) and its quantitative description at instance level (e.g., car A for user 2).

- Probabilistic descriptions are included in the conditions and consequences of executing activities. They represent stochastic behaviors of products (e.g. physical deterioration) and uncertainty in user behaviors (e.g. selection of services to achieve a specific goal). These stochastic behaviors of products and users in a PSS model can be characterized by their quantitative attribute values (e.g., failure rate) or by external quantitative descriptions (e.g. time).

Lack of the above quantitative and probabilistic descriptions indicates that quantitative and probabilistic PSS design on *Service CAD* alone is not possible. Concretely, the designer cannot perform qualitative and probabilistic PSS design on *Service CAD* from the following perspectives.

- *Timing and frequency of the occurrences of services in a product life cycle:* Occurrences of services in a product life cycle are periodical or occasional. Quantitative description is necessary to define an interval of a service, and probabilistic description is necessary to define conditions to occur a service for products, which may show stochastic deterioration behavior. *Service CAD* can describe the fact that a maintenance service necessary at an occasion of product malfunction. However, it cannot either directly define the timing and frequency of the occurrence of the service, or indirectly derive them from other descriptions (i.e. failure rate).
- *Interrelations of the occurrences of services in a product life cycle:* Occurrences of some services diminish occurrences of other services. For instance, some functional upgrading services through the replacement of modules mean that broken components in the modules are replaced. Therefore, repair of the broken components become unnecessary. *Service CAD* can describe that both functional module upgrading services and component repair services are available in case of malfunction of components. However, inclusion relations between these services are not explicitly described.

Furthermore, PSS models include multiple stakeholders with multiple perspectives (see Chapter 1). However, *Service CAD* alone cannot identify conflictive objectives among multiple stakeholders in a PSS model, nor optimize the timing, frequency and interrelations of services within the PSS model to obtain globally superior performances from multiple perspectives (Pareto optima).

4.3 Life cycle simulator

4.3.1 Simulation mechanism

The life cycle simulator developed for this study is based on a discrete event simulation technique as same as the implementations used in other studies of a product life cycle using life cycle simulation (e.g., Umeda et al. 2000; Kondoh et al. 2005; Komoto et al. 2005). The concept of life cycle simulation has been described in Chapter 2. In this section, an implementation of life cycle simulation algorithm is described. The algorithm is shown in Fig. 4.2. The algorithm consists of the main program, process objects, and product objects.

The main program generates and runs processes at the beginning of a life cycle simulation. Each process is in charge of a task in a product life cycle (e.g., production, transportation, usage, maintenance service, disposal, etc.). The tasks are generally classified into generation, deletion, and state change of products.

Each process contains two iterative loops in *run* function. The first loop represents the iteration of process activations over the entire simulation period (the macroscopic loop), while the second loop represents the iteration of task executions at a single process activation (the microscopic loop). The interval in the macroscopic loop (*d_macro*) is constant regardless of the size of task executions in single process activation, and it is far larger than the interval in the microscopic loop (*d_micro*) so that the sum of duration of the task executions at a process activation is always smaller than the interval of the macroscopic loop. This condition is removed when the simulation allows overlapping of two activations of a single process.

```
class Process(Simpy.Process):
  def __init__(self,kw**):
    Simpy.Process.__init__(self)
    self.condition= ... ; self.d_macro= ...; self.d_micro= ...

  def run(self):
    while not TERMINATE(): # macro loop for process activation
      candidates = self.determine_size()
      for i in candidates: # micro loop for task execution
        self.execute_task(candidates[i])
        sleep self.d_micro
      sleep self.d_macro-len(candidates)*self.d_micro # >0

  def execute_task(self,p)
    # -- example of program lines --
    if generate:QUEUE.append(Product)
    elif state_change: p.state_change(new_state)
    elif delete: QUEUE.delete(p)

  def determine_size(self)
    # -- example of program lines --
    candidates=[]
    for product in QUEUE:
      if product in self.condition:
        candidates.append(product)
    return candidates
```

```
class Product:
    def __init__(self,kw**) :
        ...
    def state_change():
        ...
```

```
def main()
    process={}
    for i in process_network:
        process[i]=Process(i)
        process[i].run()
    SIMULATE()
```

Fig. 4.2 Life cycle simulation algorithm implemented in *ISCL*

In each macroscopic loop, a process performs the following procedure. First, it determines the size of task executions. It is either externally defined by the designer (e.g., production plan) or determined by the number of products (candidates), whose partial state meets a set of conditions specified by the process. In the simulation *scene* is a used to define such a condition set. Second, the process iteratively executes the tasks until the number of iterations reaches the determined size. As a result, it changes the state of the corresponding products, or generates/deletes the products to/from the simulation environment. In the simulation, *queue* is used to store the product instances. State changes of products are either deterministic or stochastic.

The algorithm is well explained with an example described below. The example includes production, transportation, operation, maintenance, and disposal tools. Table 4.2 shows the contents of two functions (*determine_size* and *execute_task*) of each process. It is assumed that products appeared in the example have three attributes, each of which represents spatial, physical and temporal properties, respectively (i.e. place, condition, and age), and the interval of the macroscopic loop (or the resolution of the simulation) is a *week*, and all processes are activated every week in parallel when the size of task execution is not zero.

First a production process generates products with the initial state. A transportation process then moves products from *manufacturer* to *user*. The size of production per week is explicitly defined by *a production plan*, while the size of transportation per week is dynamically determined by the number of products at *manufacturer* and at *user*. A function *in_a_scene* returns a list of indices of products that meet the conditions specified by the function arguments. The age of products is automatically incremented with the progress of simulation. An operation process represents the usage of products by the users. Some *healthy* products get *broken* during this usage, and the failure behavior is stochastic following a reliability function, which takes the age of products as the parameter. A repair process repair *broken* products. A disposal process removes *broken* and *old* products from the simulation. The *oldness* of products is quantitatively defined by the age of products.

The order of activation of the above process in a week is explicitly defined or randomly assigned. In the case of this example, the order between the repair process and the disposal process influences on the behavior of the product life cycle. For instance, the disposal process in prior to the repair process indicates that old products are not repaired, while the opposite indicates that all products are repaired regardless of the age of products. Arbitral processes are added to the life cycle simulation by customizing the *determine_size* and *execute_task* functions.

In this implementation, products can have modularity. The modularity is represented as a direct tree structure of multiple product instances stored in respective *queue*s (Fig. 4.3). The tree structure is dynamically created or deleted by assembly and disassembly processes. All processes can access the module states of products to and change them as consequences of the task execution. Since some modules can be reused to remanufacture products, they become the member of multiple products in the life cycle. However no modules are the member of multiple products simultaneously during the life cycle simulation. In Fig. 4.6, a module (B1), which is a part of a product (A1), is reused to remanufacture a product (A4). However, two products (A1) and (A4) do not exist at the same time during a life cycle simulation. Furthermore, modules (B4-B5, C4-C6) are waiting for the assembly.

Table 4.2 Process descriptions in the example

process	conditions (described in determine_size)	consequences (described in execute_task)
Production	size = function(production_plan)	generate(product) product.place= manufacturer product.age = 0 product.condition = healthy
Transportation	s1= in_a_scene(product.place = market) s2= in_a_scene(product.place = manufacturer) demand = market_size – size(s1) supply = min(demand, size(s2)) candidates = s2[0, supply]	product.place = user
Operation	s3=in_a_scene(product.place = user AND product.condition = healthy) candidates = s3	failure_rate = function(product.age) if random.uniform(0,1) < failure_rate: then product.condition=broken
Repair	s4=in_a_scene (product.place = user AND product.condition = broken) candidates = s4	product.condition = healthy
Disposal	s5=in_a_scene(product.place = user AND product.condition = broken AND product.age >= 500) candidates = s5	delete(product)

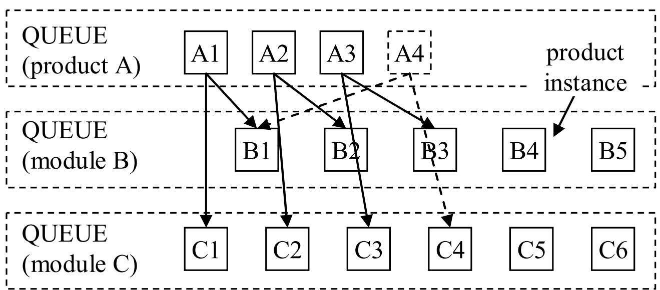

Fig. 4.3 Module structure of a product in the life cycle simulation

4.3.2 Evaluation

As a result of executing the life cycle simulation algorithm, economic and environmental performances of a product life cycle is calculated. The performances are determined by the number of activations of processes during the entire simulation period and by specific increase (decrease) of the performance per activation. The former is obtained by executing a life cycle simulation, while the latter is explicitly defined by the designer. The performance of a product life cycle *P* from single perspective *i* for single stakeholder *j* is formalized as follows.

$$P_{lc}(i,j) = \sum_{event=1}^{n} P_{event}(i,j) \tag{4.1}$$

Where, *event* represents single task execution at a process activation, and P_{event} is an *i* by *j* matrix, in which specific increase (decrease) of the performances for the stakeholders per *event* is defined. When the specific performance changes only depend on the type of processes, Equation 4.1 is simplified and the following equation is used to calculate the performance of a product life cycle.

$$P_{lc}(i,j) = \sum_{process=1}^{m} \left(\sum_{event=1}^{n} \delta_{(event,process)} \right) P_{process}(i,j) \tag{4.2}$$

$$\delta_{(event,process)} = \begin{cases} 1 & event \text{ is executed in the activation of } process. \\ 0 & \text{otherwise.} \end{cases} \tag{4.3}$$

Where, *process* represents a process in the product life cycle, and $P_{process}$ is an i by j matrix, in which specific increase (decrease) of the performances for the stakeholders per *event* in the activation of *process* is described.

Flows of elements such as money and material in a product life cycle are described as increases (decreases) of the elements among N stakeholders during an activation of processes. A closed flow of an element i among the stakeholders in a product life cycle satisfies the following Relation 4.4.

$$Closedflow(i) \Leftrightarrow \sum_{j=1}^{N} P(i,j) = 0 \tag{4.4}$$

The mechanism of evaluation by life cycle simulation is different from that of life cycle assessment (LCA).Using life cycle simulation, Equation 4.2 indicates that the performances of a product life cycle are determined based on the data about activations of processes in the product life cycle and the specific increase (decrease) of performances per activation. In comparison, LCA uses Equation 4.5 to calculate the performances instead of Equation 4.2.

$$P_{lc}(i,j) = \sum_{process=1}^{m} P_{process}(i,j) \tag{4.5}$$

Equation 4.5 indicates that LCA calculates an average life cycle scenario, which is determined by the aggregation of the average performances of single processes in a product life cycle. Furthermore, the average performances of single processes are independently determined, and the impacts of interrelations among the processes on their performances are not considered. Therefore, LCA-based evaluation methods to calculate the performances of a product life cycle are not suitable for probabilistic design of a product life cycle.

4.3.3 Implementation

The life cycle simulator developed for this study is implemented with Simpy, a generic discrete event simulation library written in Python. The process description provided by Simpy library enables complex interaction among processes such as priority and interruptions. If necessary, these features are added to the process objects of life cycle simulation. The life cycle simulator is connected with a multiple objective optimization module based on genetic algorithm (Fonseca and

Flemming1993). This feature is useful to optimize the parameter of product and process models with respect to the performances of a product life cycle.

4.3.4 Other remarks

To evaluate the holistic performances of a product life cycle, it is necessary to simulate the behavior of a number of products in a market simultaneously, instead of the linear superposition of the simulated behaviors of individual products through the entire life span. It is because some processes in a product life cycle determine the number of task executions by observing the global state of a product life cycle. For instance, the timing of executing a new function release cannot be determined by the behavior of single product, when the process description is such as "new products are released when more than 90% of products in the market have been repaired at least once". Furthermore, this process may influence on the behavior of all products in a market (e.g. disposal or upgrade of functionally obsolete products in a market).

Analytical solutions obtained by queuing theory are not suitable to the analysis of stochastic behavior of a product life cycle. It is because the behavior of a product life cycle does not follow assumptions given in the theory. For instance, distribution of time to malfunction of products does not follow an exponential distribution, which indicates the timing of a process occurrence is independent of the history of the process occurrences. Therefore, a maintenance service is planned based on the failure history and on the failure rate determined by reliability experiments.

4.4 Integration

As illustrated in Fig. 4.1, quantitative and probabilistic descriptions are added to a PSS model developed on *Service CAD* so that its performances are analyzed from a holistic perspective based on life cycle simulation technique. Before adding these descriptions, the PSS model is converted to an executable life cycle simulation model.

4.4.1 Model conversion

To perform the conversion of a PSS model developed on *Service CAD* into an executable life cycle simulation model, correspondences of model elements between *Service CAD* and the life cycle simulator should be clarified. Table 4.3 shows the correspondences of those elements. The conversion process consists of the following two steps.

- Creation of the class name space (processes, products, and performance indicators) for life cycle simulation based on static elements and relations in a PSS model on *Service CAD*.

- Generation of program lines of the process classes for life cycle simulation using the descriptions about conditions and consequences of corresponding activities on *Service CAD*.

The elements and relations shown in Table 4.3 are static nodes and edges of a PSS model on *Service CAD*. These are used for the first conversion step. The correspondences are given as follows.

- Performance indicators are obtained from service goals and quality criteria defined on *Service CAD*.
- Process class in the life cycle simulator is used to represent activities defined on *Service CAD*.
- Product class in the life cycle simulator is used to represent constituents defined on *Service CAD*.

The above correspondence indicates that the concept of product class in life cycle simulation is extended so that it can represent all constituents in a service environment. It also indicates that the concept of process class in life cycle simulation is not the activity of a service provider (receiver), who is in charge of a specific task in a product life cycle, rather the activity that requires the existence of multiple constituents in a service environment. This correspondence is natural from a perspective of PSS design, because it does not require preliminary clarification of the roles of constituents as providers, receivers, channels and contents, which will be gradually determined during design process. For instance, a clerk in context of first food delivery service can be an automatic vending machine or a parson. This person can be treated as a service provider to deliver kindness to customers, a service channel owned by a franchise, or a service content delivered by a temporally staffing agency in a PSS model.

Relations among elements in a PSS model have the following correspondences. Has-parameter and has-relation define the parameters and relations of constituents (represented by the product class). The values of parameters are given at the instantiation of constituents, while those of relations are *False* at the instantiation. Decomposition relations among service goals define functional relationships among the corresponding performance indicators. Relations between quality criteria and the parameters of constituents also define functional relationships between performance indicators and the corresponding parameters of constituents. Temporal relations among activities define the partial order of activation of process instances.

Relations among constituents are more general than the modular structure of products in a life cycle model. Simply stated, the module structure is a direct tree structure, while relations among constituents form a network structure. This generalization introduces complexity in managing a set of constituents, which belongs to a *scene*, or a particular state in a service environment. This complexity will be discussed in Section 4.4.2.

The rest of correspondences in Table 4.3 are descriptions about conditions and consequences of activities to be used to generate program lines of process classes for life cycle simulation.

Conditions of activities defined on *Service CAD* are used to form a *scene*, which specifies a set of constituents indicating a particular state of a service environment. It is done by using the condition descriptions as parameters of the *in_a_scene* function appeared at *determine_size* function of the corresponding process. The form of the *scene* derived from *Service CAD* is different from the *scene* used in the life cycle simulator (see Section 4.2). In the life cycle simulator, the *in_a_scene* function returns a list of indices of products that meet the condition defined by its arguments. The *in_a_scene* function to deal with multiple constituents should provide a list, whose elements are the list of *constituent-index* pairs. As already mentioned in the generalization of the module structure to represent generic relation among constituents in a service environment, this extension of the form of *scene* also introduces complexity running life cycle simulation. This complexity will be discussed in Section 4.4.2.

Both conditions and consequences of activities defined on *Service CAD* are used to generate program lines at *execute_task* function of process instances in life cycle simulation. It is done by replacing each assertion in these descriptions into one of the primitive commands defined in life cycle simulation (Table 4.4).

Table 4.3 Correspondence between two model representations

	The PSS model used on *Service CAD*	The life cycle model used on the life cycle simulator
Nodes	specifications (goal instances, quality instances)	performance indicators
	activity instances	process instances
	constituents (providers, receivers, channels, contents)	product instances
	parameters (of constituents)	attributes (of product instance)
	relations (between two constituents)	attributes (of two product instances)
Edges	has parameter / has relation	definitions of attributes of constituents
	a specification relation (a constituent and a specification)	not defined
	a relation between two service goals	a function relation
	a relation between a quality and a parameter	a function relation
	temporal relations among activities	a partial order of process activation
Execution conditions of activity and process instances	existence of a constituent	existence of a product instance
	existence of a relation between constituents	a Boolean condition of an attribute
	a qualitative condition of a parameter value	a quantitative condition of an attribute value
Consequences of activity and process instances	goal realization	increase the value of a performance indicator
	quality evaluation	statistic evaluation of a performance indicator
	changes of a parameter value [inc, dec, set]	changes of a quantitative attribute value
	generations and deletions of a relation	changes of a Boolean attribute value
	generations and deletions of a constituent	generation and deletion of a product instance

Value changes of performance indicators are performed internally. The performance indicators derived from service goals are measured by counting the number of tasks executions in the activity that realizes the respective service goals. Those derived from quality criteria are measured by observing the attribute values of instances, which are related with the respective quality criteria. The measurement of performance indicators derived from quality criteria is statistic, because multiple constituents with different attribute values exist in a life cycle simulation. For this reason, the average and the variance of the attribute values collected from the multiple constituents determine the values of quality-based performance indicator. A set of constituents included in the statistic evaluation can be filtered by specifying a *scene* for the evaluation process, and other static values such as the maximum or the minimum are also added.

Table 4.4 Primitive commands defined in the life cycle simulator and their correspondences to activity descriptions defined *Service CAD*

Activity descriptions	Primitive commands
existence of a constituent (from condition)	call_constituent(constituent)
changes of a parameter value [inc, dec, set]	set_value(constituent, parameter, new_value)
generation of a relation	add_relation(constituent1, constituent2, relation)
deletion of a relation	remove_relation(constituent1, constituent2, relation)
generation a constituent	generate_constituent(constituent_name)
deletion of a constituent	remove_constituent(constituent)
	value = get_value(constituent, parameter) * This command is used to add qualitative and probabilistic description to life cycle simulation model.

4.4.2 Dynamic scene instance manipulation

In order to conduct a life cycle simulation based on the mechanism proposed in the previous section, it is necessary to identify a set of products that belong to a specific state. The life cycle simulator defines *scene* as a set of the conditions to specify a product set, and defines *in_a_scene* function to find products in a specific *scene*. The life cycle simulation of a PSS model defined on *Service CAD* is different from the life cycle simulation that only deal with a number of products in a market in that it considers relations among a number of products, users, and service providers in a service environment.

Figure 4.3 shows a slice of life cycle simulation of a PSS model, which illustrates the relations between cars and stakeholders appeared in a shared-service or function-sales based business model. Constituents of the service environment are a manufacturer, cars, users, and owners. Users and owners belong to a constituent type called person, because a person can become a user and/or an owner. As shown in Fig. 4.3, relations between cars and the other constituents have variety. Consider two activities *use* and *repair* are introduced to change the states of the service environment. Each activity uses a *scene* to specify a set of instances of the constituents that satisfy certain conditions. The scene instances for the use activity indicate that a car (C2) is intensively used than the others. A car (C3) is not included in the scene instances for the repair activity, because the owner of the car, which may pay the service fee to the manufacturer (M1), is not specified in the service environment.

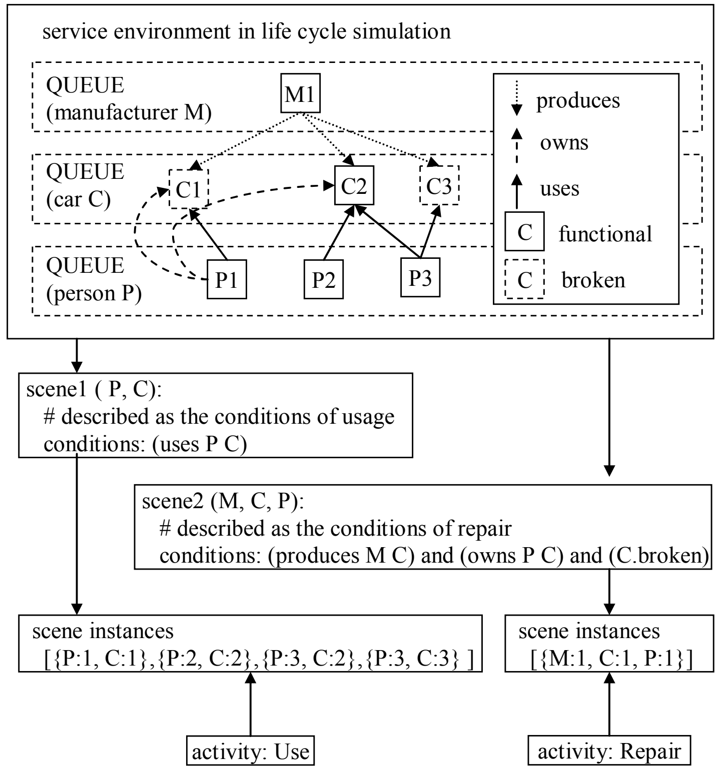

Fig. 4.3 Scene descriptions of a service environment for life cycle simulation

As described at the previous sub section and as shown in the above example, a life cycle simulation of a PSS model on *Service CAD* has higher complexity in representing members of a *scene* (*constituent-index* pairs rather than *product* indices) and relating constituents in a service environment (*network* of constituents rather than *direct tree structure* for product modularity). Given the complexity of evaluating *n* products in a market with the *in_a_scene* function is *O*(n), the complexity of evaluating a service environment including *m* constituents, each of which has *n* instances, with *in_a_scene* function is *O*(n^m). Modularity of products does not increase the complexity at an exponential order, because the modularity is a direct tree structure, which does not allow overlapping (i.e., a module can belong to a product at a time). In order to manage complexity regarding scene manipulation in a life cycle simulation, it is useful to dynamically trace (register and remove) the membership of all scenes during the entire life cycle simulation instead of the iterative evaluations at necessary occasions.

Figure 4.4 shows the proposed algorithm to dynamically manipulate scene instances during a life cycle simulation of a PSS model. This algorithm is placed at the end of the *execute_task* function in Figure 4.2. The objective of this algorithm is to reflect the resulting state transitions of a service environment at a task execution to addition and removal of scene instances defined on the service environment. It consists of three sub functions as follows.

Manipulate is the main function of this algorithm. It takes a scene instance *si* as input. A *si* consists of a set of constituent instances, or constituent-index pairs (see Fig. 4.4). Some of these instances are labeled before this function is called. The types of labels are determined by the resulting state transitions of a service environment as the task execution. Concretely, generated, initialized and modified (in terms of their attributes and relations with others) instances are labeled *modified*, and deleted instances are labeled *deleted*. The following procedure is performed for each *scene* defined in the PSS model. Unless there is overlapping of the constituents appeared in the *scene* and labeled constituents in *si*, no instance manipulation is necessary with respect to this *scene*. When there is the overlapping, the *match* function is called to perform the manipulation described shortly. When some constituents in *si* are deleted from the simulation, all scene instances that include the deleted constituents are removed from the simulation.

```
manipulate(si):
  si := {e_a : index(e_a), e_b : index(e_b), ...}
  for each scene ∈ ALL_SCENES:
    if not nodes(scene) ∧ (modified(si) ∨ deleted(si)) =∅:
      match(si, scene)
      if not nodes(scene) ∧ deleted(si) =∅:
        for si′ ∈ instances(scene):
          if si′ includes index(deleted(si)):
            remove(si′, scene)
```

```
extend(si, scene):
  si_e =[]
  for rel ∈ relations(scene):
    if rel is neighbor of modified(si):
      e_in : e_in ∈ modified(si)
      e_out : e_out ∉ modified(si)
      for each e ∈ QUEUE[e_out]:
        if exists([rel, e_in, e]) ∨ exists([rel, e, e_in]):
          si_ex = si.update({e : index(e)})
    si_ex.append(si_ex)
  return si_ex
```

```
match(si, scene):
  if state(si) ∈ scene:
    register(si, scene)
  elif state(si) ∉ scene:
    remove(si, scene)
  else:
    for each si_e ∈ extend(si, scene):
      match(si_e, scene)
```

Fig. 4.4 An algorithm for dynamic scene instance manipulation

Match function evaluates whether a scene instance *si* belongs to a *scene*. For the evaluation, the state of the minimal service environment including all constituents in *si* is observed. If the state of the service environment satisfies all requirements specified by *scene*, then the constituent instances in *si* relevant to *scene* is registered as a new instance of *scene*. If the state violates at least one requirement, instances of *scene* including the violating instances are removed. When the description of *scene* contains more constituents than those in *si*, information about the state of the service environment including the constituent instance in *si* is not sufficient for the evaluation. In this case, the constituent instances related with those in *si* are added to *si* in order to increase the state information necessary for the evaluation of *scene* Addition of these constituent instances are performed by calling the function *extend* described below.

Extend function constructs extended scene instances based on a scene instance *si* using the description of *scene*. Each extended scene instance constructed by this function consists of the constituent instances in *si* and some additional constituents. The type of additional constituents is determined by relations between two constituents defined in *scene*. Some relations are boundary relations of si, because an instance of one constituent in a relation is in *si* and the other is not in *si*. This function searches constituent instances that are related with the constituent instances in *si* at its boundary. Since constituent instances in a service environment have many to many correspondences, multiple extended scene instances are derived from a scene instance *si*. *Match* is called with each of extended scene instances as its argument to evaluate if extended scene instances belong to *scene*.

4.4.3 Additions of qualitative and probabilistic descriptions

Qualitative and probabilistic descriptions are added to the generated program lines at the consequences of process instances. The contents of quantitative and probabilistic descriptions to be added have been described in Section 4.2.3. The descriptions consist of *if-then* statements and *random* variables supported by python.

4.5 Conclusions

In this chapter, *ISCL*, an integration of a service CAD tool and a life cycle simulator has been proposed as a CAD/CAE tool for systematic PSS design. First, limitations of *Service CAD* proposed in the previous chapter in quantitative and probabilistic PSS design from a life cycle perspective have been identified. Following the review in Chapter 2, life cycle simulation technique has been selected as the technique to be integrated into *Service CAD* in order to compensate its limitation in dealing with probabilistic and quantitative PSS design information. For the integration formal correspondences among the elements of a PSS model on *Service CAD* with those in a life cycle model for life cycle simulation had to be identified. Furthermore, a life cycle simulation mechanism to deal with flexible description of a PSS model on *Service CAD* had to be considered.

Integration of *ISCL* with other modeling methods and tools will be necessary when researchers of the PSS concept hypothesize new propositions that potentially improve the design of PSSs, and when designers of PSSs find necessity of methods and tools that potentially improve the productivity of design process. Nevertheless, the integration presented in this chapter was fundamental to challenge the identified issues under the given research scope shown in Chapter 1. Under the context of this study, the following remarks regarding the design information used at specific tasks in systematic PSS design process have been obtained through the process of integration.

Remarks related to the research question 1b

Quantitative and probabilistic information is necessary to describe such PSS design concepts as shared services, while considering uncertain user behavior and stochastic product deterioration. Mechanism of *ISCL* has shown that such information can be added to the description of PSS design concepts. It is still necessary to identify design information that are crucial in evaluating the design concepts, since the degree of importance of quantitative and probabilistic information in evaluating the performance and in redesigning the concept based on the evaluation, may be different. Modeling of such information and the evaluation of the importance will be discussed in the following chapters.

Remarks related to the research question 2a

Mechanism of *ISCL* has shown that quantitative and probabilistic information can be added to the description of PSS design concepts, and the life cycle simulation technique explicitly reflects qualitative and probabilistic information on the performance of design concepts. Further study for alternative computer-aided methods for PSS design concept evaluation is required when other types of design information are considered necessary, and when the designers generate and evaluate PSS design concepts based on a design principle other than the one presented in hypothesis 3 of this study in Chapter 1.

Remarks related to the research question 2b

Integration of *Service CAD* with a life cycle simulator for computer-sided PSS design does not only indicate monotonic increase of information that can be computationally handled in PSS design process. It also indicates that division of the tasks of PSS designers in a design team, because different types of expertise are necessary to conduct modeling on *Service CAD* and evaluation using a life cycle simulator. This task distribution is different from that proposed in Chapter 3, which includes task divisions by experts with respect to individual product and service domains. The division proposed here is based on the expertise about operating these computational tools. Limitation of PSS designers in conducting all design tasks in computer-aided PSS design environment observed at education of PSS design is discussed briefly in Chapter 8.

5 Considering services in product life cycles

In the previous chapters, *ISCL* (integration of *Service CAD* and life cycle simulation) has been developed in order to answer the rest of research questions (RQ1b, RQ2a, and RQ2b). ISCL utilizes the formalization of design information about PSSs proposed in Chapter 3. The formalization was necessary to provide computational supports in systematic generation of PSS design concepts. It has also restricted the types of design information used in the design process. In Chapter 5, Chapter 6, and Chapter 7, answers to these questions are found in context of quantitative evaluation of PSS design concepts. In these chapters, the types of design information that are critical in modeling and evaluating PSSs are investigated. The investigation is conducted with case studies using *ISCL*. In Chapter 5, services in a life cycle of products are analyzed. The products are durable and capital goods, for which services are introduced to give profits for manufacturers as the main stakeholders of PSSs. The design of services including functional sales, shared services, maintenance, function upgrades, is analyzed. In the analysis, user behavior and price-based competitions are considered as part of design information to determine the performance. This chapter is concluded with presenting the type of design information implicit but critical in determining the performance, and the identified utility of *ISCL* to model and evaluate PSS design concept using such information.

5.1 Introduction

In the previous chapters, *Service CAD* has been developed, and it has been integrated with life cycle simulation (*ISCL*). The main function of *ISCL* is to support PSS design process by utilizing design information about PSSs. The formalization to describe a PSS model in *ISCL* has restricted the types of design information used in the design process. The restriction is inevitable for the realization of computational supports presented in Chapter 3 and Chapter 4. In this chapter, design information about PSSs used for the modeling and evaluation of services in a life cycle of products is investigated.

The investigation in this chapter focuses on services in a life cycle of such durable and capital goods as washing machines, computer embedded systems, and automobiles. These services can provide additional value to product users and additional profit to the manufacturers of products other than the ownership delivery of products. Maintenance and functional upgrading services of these products are crucial in increasing physical and functional life time of such products in a technology driven market. These services are considered environmentally friendly not only because they increase physical and functional life time, but also because they can be integrated with end-of-life options. Type of contracts between product users and manufacturers of these products can be designed to improve the environmental performance from a life cycle perspective. Examples of the designed contracts are pay-per-function based service and shared service contracts.

In academia, services in a product life cycles are studied by the researchers in the field of Industrial Product Service Systems (Transregio29, 2008). The motivation of the study is summarized as follows. First, a product life cycle consists of multiple stakeholders that deliver services to product users, and explicit consideration of their corporation and competition is crucial to design appropriate distribution of service fee and costs among them. Second, product design and service design in a product life cycle influence each other. Functions of products are service contents delivered to product users. When delivered to users, products can become service channels that enable, enhance, and amplify services for product users during the usage of products. Content and timing of services necessary during the usage of products such as maintenance can be designed based on the expected (deterioration) behavior of products at customer's hand. Third, service design from a PSS perspective concerns systemic relations among products and services as system elements in a product life cycle.

This chapter includes three simulation-based case studies about services in a life cycle of washing machines, computer embedded systems, and automobiles. Although each study analyses the service design from a PSS perspective focusing on different characteristics of these services, the common purpose of these case studies is to identify the types of design information necessary in the modeling of PSSs and the evaluation of the performances (in relation with the research question 1b).

Furthermore, case studies in this chapter mainly focus of the performance evaluation of the service offerings from an economic perspective. This does not mean that *ISCL* cannot deal with the evaluation of services from such perspectives as environment, culture, and social responsibility. Do do so, performance indicators in terms of those perspectives and design information that relates the services with the indicators are necessary. Development of performance indicators from those perspectives, and evaluation of the services presented in the case studies from those perspectives are out of the focus of this study. Recommendations to extend these tools for those perspectives are summarized in Chapter 8.

In Section 5.2, four long-term business models using washing machines are compared (conventional sales model, function sales model, shared service model, and commercial (function centralized) model). First, in the conventional sales model, washing machines are treated as service *contents*. In the other models, washing machines are treated as service *channels* to deliver their *function*, and they are different in terms of the roles of the manufacturer and intermediate service providers, which determine financial flows in these business models. In order to compare the financial flows derived from four business models this study introduces *a function unit*, as employed in life cycle assessment (LCA) based evaluation methods.

In Section 5.3, maintenance and functional upgrading services in the life cycle of computer embedded systems are analyzed from a manufacturer's perspective. Maintenance in the product life cycle may be provided when a crucial physical failure and/or functional obsolescence occurs at a particular module level. How often this is provided differs with the module type. Some mechanical components must be repaired often with fewer functional upgrades, whereas computer software showing no physical deterioration may have to be upgraded frequently. Design of combinations of these services can decrease life cycle costs by decreasing the need for expensive service (e.g., obsolete computer hardware and software maintenance) by increasing cheap and timely service, such as regular software and hardware maintenance and upgrading. This study analyzes a method to generate alternative combinations of these services, and evaluate the life cycle costs of the generated alternative services.

In Section 5.4, maintenance in a life cycle while varying user behavior in a competitive environment is analyzed to study the economic feasibility of integration of maintenance activities with the other services in a product life cycle from an auto manufacturer's perspective. The feasibility can depend on user preference for specific service content and purchase timing, and on the types of service content provided and discounted by competitors. A comprehensive maintenance package must be designed considering the diversity of user behavior if sales are to be raised over those of on-the-spot maintenance.

In Section 5.5, this chapter is concluded with presenting the identified types of design information useful in modeling PSS design concepts and in evaluating the performances of the concepts.

5.2 Comparing PSS business models

In this case study, the economic performance of multiple PSS business models are compared from a life cycle perspective.

Existing PSS studies often employ *functional unit* to evaluate the performance of PSSs. In the performance evaluation based on functional, it is assumed that all products have identical behavior in the market and end of life process. This approximation does not only fail effective analysis of PSSs, but also constrain the design of PSSs, in which the behavior of individual products is taken into account. In this study, it is therefore assumed that products in a business model are individual instances. In other words, states of products can vary in the life cycle depending on the usage and maintenance patterns, besides due to stochastic nature of deterioration. Effects of such fluctuation on economical and environmental performance must be considered especially to evaluate PSSs correctly from life cycle perspectives. Furthermore, modularity of products is assumed. A module has a number of components, each of which has such original properties as physical lifetime, use lifetime, value lifetime, market value, and life cycle options including reparability, reusability, and recyclability.

Because the PSS concept deals with product life cycle, the performances of PSSs should be evaluated from a life cycle perspective. As pointed out by Mont

(2002), there are many fragmental PSSs solutions, but few are completely designed from a life cycle perspective. In other words, these solutions cannot relate product design determined at the early phase of a life cycle with the performance of service at latter stages in the life cycle. Based on the assumption that products in a business model as individual instances, the performance of a business model from a life cycle perspective is calculated by aggregating the performances of a life cycle of single products, which has fluctuations due to stochastic deterioration. This assumption is related with the other assumption about modularity. For instance, the end of life policy of home appliances can determine appropriate module structure of the products (Umeda et al. 2000; Fujimoto et al. 2003).

A complete PSS solution can be realized by integrating several services based on the PSS concepts (e.g., functional sales, shared services). The integration is useful when a PSS solution is not superior to traditional product sales from an economic perspective (Bartolomeo et al. 2002). The integration is possible when multiple PSS concepts may not have contradictive performance with one another (Hanssen 1997).

Toward realization of a PSS design concept, collaboration among the stakeholders involved in the design concept is necessary (i.e. users, governments, and manufacturers). Among others, manufacturers play a crucial role as active decision makers to select and realize a PSS design concept among potential design alternatives, while users and governments constrain possible alternatives in terms of function requirements and legislation. Recent highlights on extended producer responsibility (EPR) and Integrated Product Policy (IPP) urge manufacturers to redesign products and product life cycles to take initiatives concerning sustainability (Tojo 2004). Accordingly, the impact of manufacturers' attitude to sustainability is not minor. For manufacturers, the main concern is to translate the PSS concept into specific services in life cycles of their products. To do so, they need to roughly identify potential advantages and risks of concrete service design in advance of implementation.

In this study, four business models based on the PSS concept are analyzed with *ISCL*. These models are compared in terms of distribution of benefits of the involved stakeholders by simulating service occurrences from a life cycle perspective.

5.2.1 Modeling shared services and functional sales

In this example, a business model to provide function of washing is analyzed. Four alternative business models are employed to compare the performance from environmental and economic perspective:

1. The traditional model provides function of washing to customers by selling washing machines. There are not really services involved except for those associated with product life cycles, such as maintenance, upgrade, and recycling/remanufacturing services.
2. In the functional sales (pay-per-use) model, washing machines remain properties of a manufacturer which provides function of washing to customers and guarantees accessibility to the washing function. Products

and their life cycle in these two models are identical. However, difference arises in the flow of ownership and respective cash flow. Besides those associated with product life cycles, enabling type service is involved.
3. The sharing model introduces another service provider, who possess washing machine and provide the function to customers (coin= operated laundry model). Here, convenience/enabling type service is involved.
4. Finally, the commercial (laundry service) model employs another service provider, who operates the washing machine instead of customers, and receive service fee from the customers. This model is an example of proxy type and convenience type service (Tomiyama et al. 2004).

All four models (including the traditional model) are potentially categorized as instances of the same PSS. However, environmental and economical performances of each business model may be different. Through analysis of this case study, we clarify these differences and identify critical design parameters to attain better performances.

Simulation setup

First, elements of the PSS of washing function according to the formulation in the previous subsection are defined. Figure 5.1 describes the overall simulation procedure.

- *Service:* Function of washing for 15 years
- *Service receiver:* 1,500 customers, each of who wash 1,000 kg of clothes per year.
- *Service provider:* In the traditional and functional sales models, the manufacturer provides the service. Other two models employ another intermediate service provider as the owner and/or operator of washing machines.
- *Product:* We assume that there are three types of washing machines: Household (H-type), Community (C-type), and Professional types (P-type). H-type washing machines are used for the traditional model and the functional service model, the C-type for the sharing model, and P-type for the commercial model.
- *Product structure and property:* Components of a washing machine are categorized into operation-critical modules (m1) and lifetime-critical modules (m2). For the sake of simplicity, reliability of the washing machines is measured in terms of number of operations and lifetime of respective modules. Table 5.1 summarizes parameters of washing machines.
- *Events in the business models:* Types of available events depend on the property of products. For instance, disassembly and reuse events are available, if components of washing machine are reusable. Table 5.2 shows relations of events in the business models with the responsible actors.
- *Resource and value:* In this case study, we analyze a PSS with regard to environmental and economical performance perspectives. Table 5.3 defines relevant life cycle costs of all type of the washing machines. It is assumed that resource consumption (e.g., energy, water, detergent) during operation phase is proportional to the weight of washed clothes.

Table 5.1 Product Parameters

	H-type	C-type	P-type
Product parameter			
Value Lifetime [year]	10	5	3
Operation capacity [operation/week]	5	100	125
Capacity [kg/operation]	4.0	6.0	12.0
Module parameter			
Introduction of wear out phase (m1) [operation]	10000	30000	30000
Failure rate before ware out phase (m1) [per operation period]	0.00001	0.00001	0.00001
Introduction of wear out phase (m2) [operation]	500	500	500
Failure rate before ware out phase (m2) [per operation period]	0.0001	0.0001	0.0001
Life cycle options			
Repair	Yes	Yes	Yes
Module reuse	No	Yes	Yes

H-type: Household-type, C-type: Community type, P-type: Professional type

```
WM:= Washing Machine
Iteration (WM at market)
  Determine operationsize
  Iteration (operationsize)
    Wash
    IF (machine is broken
     AND repaircount<threshold (=3)
     AND lifetime<ValueLifeTime):
      THEN toRepair
           repaircount +=1
    ELSE:
      toDischarge
Iteration (WM discharged)
  IF (Module is reusable)
    Disassemble WM
    Iteration (Module)
      IF Module is not worn out:
        THEN toReuse
      ELSE:
        toDispose
  ELSE:
    toDispose
```

Fig. 5.1 Procedure of simulation

Table 5.2 PSS-events and responsible actors

	Traditional	Functional sales	Sharing	Commercial
Manufacture	Manufacturer	Manufacturer	Manufacturer	Manufacturer
Operate	User	User	User	Owner
Repair	User	Manufacturer	Owner	Owner
Discharge	Manufacturer	Manufacturer	Manufacturer	Manufacturer
Modular reuse	-	-	Manufacturer	Manufacturer

Table 5.3 Life cycle costs and prices

	H-type	C-type	P-type
Module production cost (m1)	0.2	0.4	0.4
Module production cost (m2)	0.2	0.2	0.4
Assembly cost	0.2	0.2	0.2
Repair cost	0.2	0.2	0.3
Reuse cost	0.15	0.15	0.15
Disposal cost	0.05	0.05	0.05
Purchase price	1	2	2.5
Ownership license	0.1	0.1	0.1
Operation fee	0.0004	0.0006	0.0012
Repair fee	0.2	0.3	0.5
Collection fee	0.05	0.05	0.05

H-type: Household-type, C-type: Community type, P-type: Professional type

5.2.2 Results and Analysis

Figure 5.2 describes the results of the simulations. The top figure describes the result of the traditional and functional models. These two models are evaluated with the identical life cycle simulation parameters, because the replacement of the ownership and allocation of alternative life cycle costs should not change the structure and properties of washing machines. Therefore, the same event occurrences are applied to evaluate performance of these models. Variations of performance between the two models are solely due to the differences in the value.

On the other hand, the sharing and commercial models use different types of washing machines, which have different operational capacity, deterioration phenomena and life cycle options. These differences result in respective occurrence of events and the specific performance of individual events.

The accumulated number of events in the respective business models during a life cycle simulation is shown in Figs. 5.3, 5.4, and 5.5, respectively. The economic performances of each actor for all business models (Fig. 5.6) are calculated with costs and prices of specific events shown in Table 5.3.

The simulation results show that the simulated four business models have unique properties from economic perspectives of different actors, although they provide the same amount of service to customers over the entire simulation period.

Assumed that the environmental impact is evaluated by the number of event occurrences alone, the functional service model cannot fundamentally contribute to the reduction of environmental impacts, although it contributes to improving economic performance. Compared with the functional service model, the sharing and the commercial models improve the environmental performances. In the sharing model, considering influence of reusing modules, the decrease on the number of respective event occurrences achieves above factor 10 (30 in production, 15 in assembly and 10 in disposal). In the commercial model, these factors are doubled.

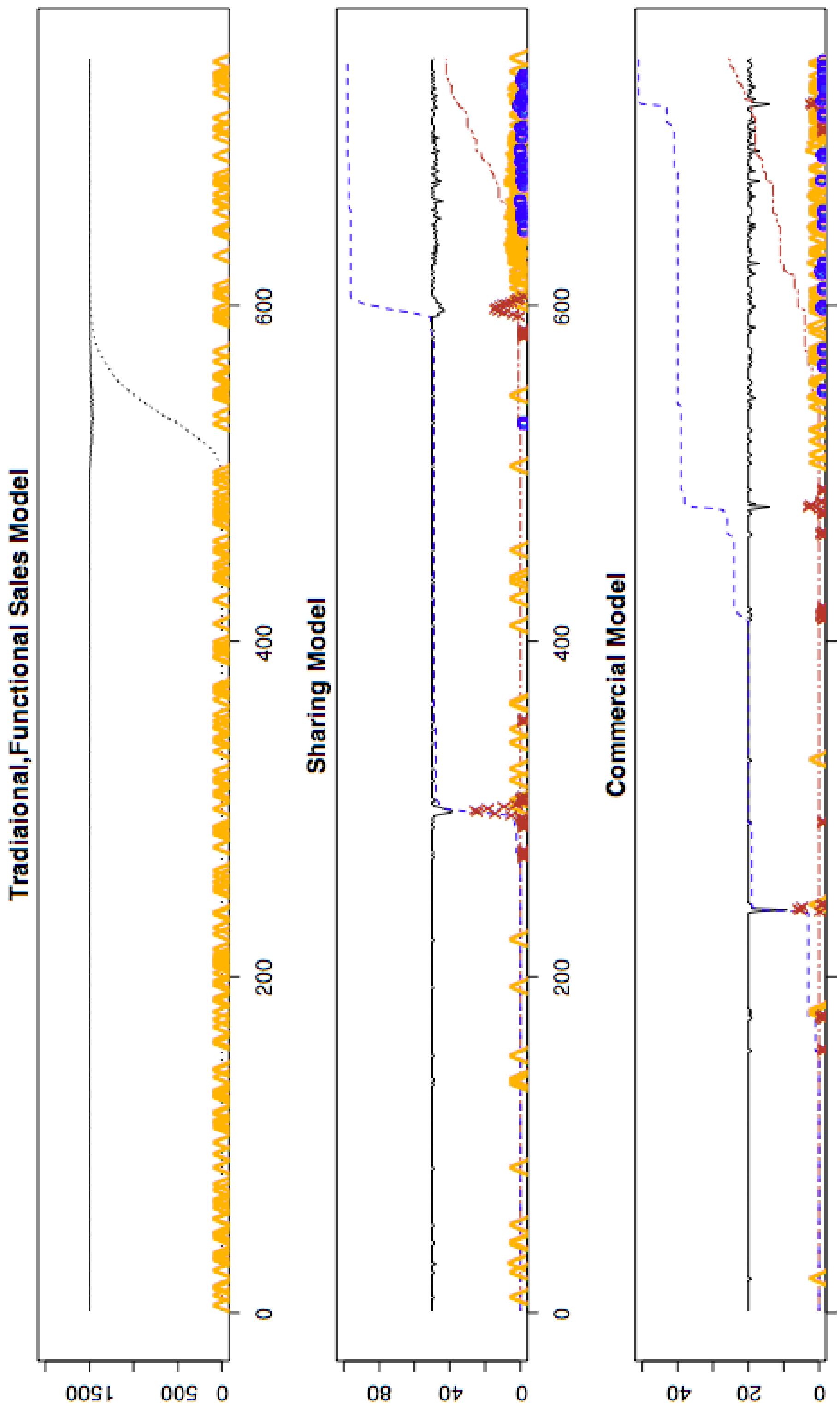

Fig. 5.2 Simulation results through the entire simulation period: Washing machine in the market, disposed and repaired (solid line, dot line, and '^'), Disposed and reused module 1 (dashed, 'o') and module 2 (two dash, 'x')

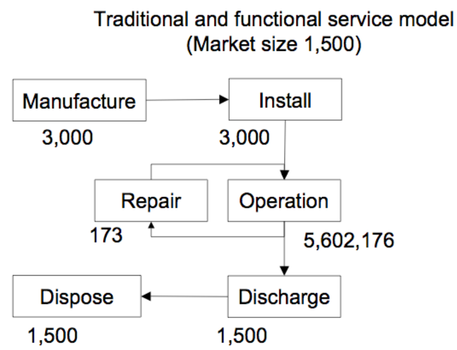

Fig. 5.3 Simulation results of the traditional model and functional sales model

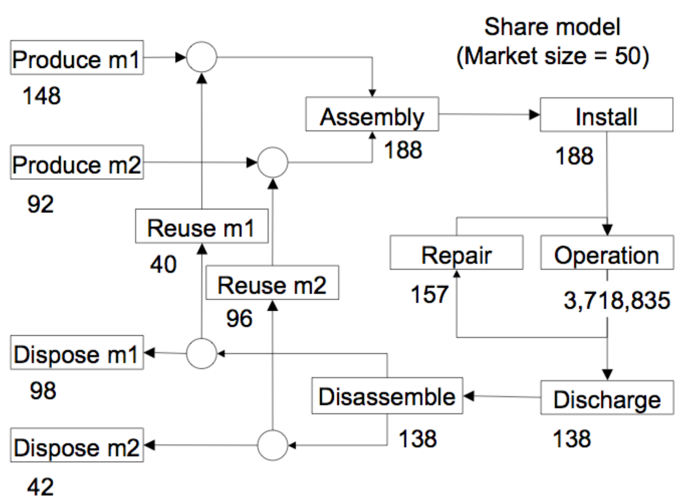

Fig. 5.4 Simulation results of the sharing model

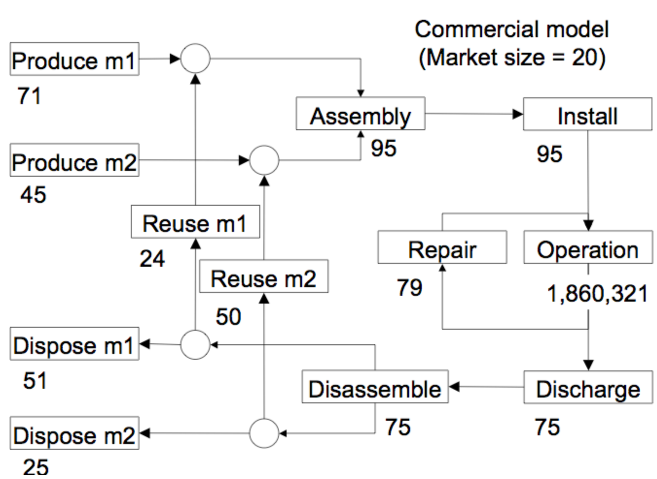

Fig. 5.5 Simulation results of the commercial model

Total economic performance in Fig. 5.6 indicates the sum of all financial scores of all actors. This amount is considered equal to the total cost to maintain the washing service to meet the demand of the customers. This indicator can be replaced by any other indicators such as environmental impacts. Efficient usage of washing machines is a necessary condition to decrease the total cost, if the demand for the service remains constant.

The simulation model was built with an assumption that the total amount of the service demand is constant. The total service supply is determined by the number of washing machines and the capacity of individual washing machines. The result shows that the total costs of the traditional and the functional sales models are bigger than the other models. It is because, the cost is determined by the number of washing machines distributed to individual users, and the capacity of the washing machines are bigger that the amount of clothes put at individual machine usage. Although introducing extremely low capacity washing machines can decrease the amount of service supply, it may damage the brand image of the manufacturer and discourage technological development. Another possible alternative PSS can be to increase the lifetime of critical module (m2) in the functional sales model. However, extension of lifetime must correspond to the value lifetime and technological development of washing machines.

What prevents manufacturers and customers from selecting these sustainable business models besides obvious customer’s inconvenience? This is because both the sharing and the commercial models require the third party, who provides infrastructure to utilize washing machines efficiently but instead “steals” considerable amount of profit from manufacturers. Unless the third party is willing to pay a compensation fee to the manufactures, this model is not attractive to the manufacturers.

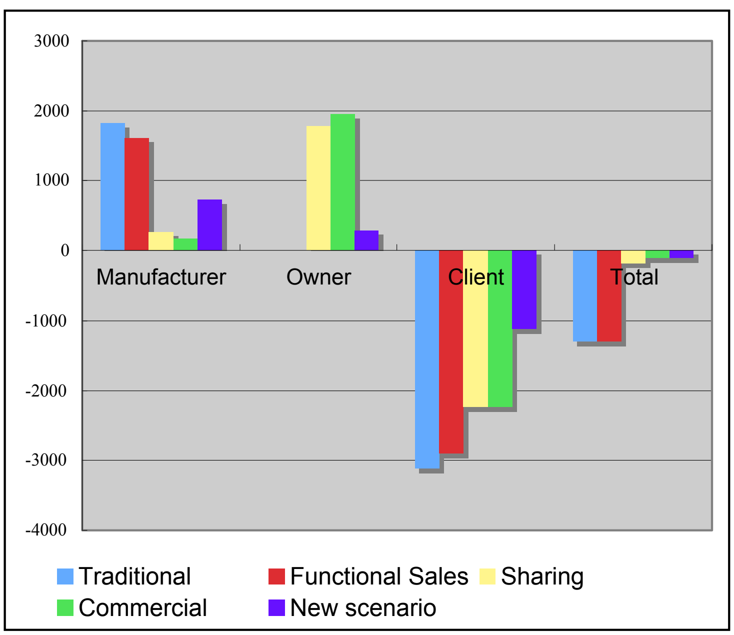

Fig. 5.6 Resulting economic performance with respect to the actors in the business models

Adjustment of economic performances per single events has potential to overcome difficulty to realize a sustainable business model. For instance, manufacturers ask a third party to install their professional washing machines. The third party can ask a constant contribution fee from the manufacturer, instead of paying a license fee. At each operation, a customer pays an operation fee to the manufacturer. This may attract customers due to feasible reduction of washing cost. Finally, this example provides a “win-win” situation for both manufacturers and customers from environmental and economic perspectives. Performance of this example is shown in Fig 5.6 as “new scenario”.

5.3 Integrating functional upgrading services

In this sub section, integration of functional upgrading service into services in a life cycle of such computer-embedded products as manufacturing systems, medical diagnosis equipment, and industrial machines controlled by an embedded computer system, is analyzed. These products last physically longer than 10 years. However, often, computer systems used in those systems suffer from technological obsolescence. For instance, an operating system (OS) 10 years ago is neither sold nor maintained nowadays. A new OS does not support an old bus standard. Rapid developments of the bus standards make it impossible even to purchase repair components and peripherals.

Total cost of ownership (TCO) and availability of those products through the life cycle are of being user’s primary concern. Functional upgrading service can potentially decrease TCO, while improving functions and maintaining availability. For instance, functional upgrading service decreases varieties of the versions of computers embedded in the products in market. This can save maintenance costs by decreasing the number and variation of spare parts and the maintenance of old software systems, which often becomes even impossible.

For manufacturers, design of functional upgrading service is a means to optimize life cycle costs, while considering the overall users’ benefits (e.g., TCO, availability and newness of functions). The service can be integrated with maintenance. The service can vary from just software updates to replacement of modules instead of the entire system. Furthermore, the performance of service is also influenced by market conditions (e.g., preference of the market for upgrading service) and technology conditions (e.g., interval of new function releases).

Furthermore, these products require continuous upgrades of sub-systems (e.g., electric and software elements) due to rapid technology advances, while the system as a whole has long physical lifetime (Westkaemper and Osten-Sacken 1998). A manufacturer needs to offer various upgrade and maintenance services with optimized life cycle costs. Each type of service contract has a unique service option, when hardware and software become obsolete or broken. These result in different storage and maintenance costs. For users, the trend is to consider TCO including operational costs, maintenance costs and functional upgrading service. Under these circumstances, generation and quantitative evaluation of alternative service options for functional upgrading service is not a trivial task.

In this sub section, *ISCL* is used to systematically generate the service designs (i.e. PSS design concepts) and evaluate the life cycle costs of the generated designs.

5.3.1 Modeling integrated service offerings

Advanced concept generation

The designer defines a PSS model to offer functional upgrading service of a computer-embedded system on *ISCL*. Although the supports by *Service CAD* to generate PSS design concepts (see Chapter 3), this subsection provides an advanced usage of the supports. Alternative activities to perform this functional upgrading service are generated with this advanced support.

The conditions and consequences of upgrading and maintenance services are listed in Table 5.4. These conditions show that releases of products, hardware and software with new functions lead to replacement or upgrading services, while malfunctions of those components require maintenance services. These services may deliver other service contents as a consequence. For instance, computer upgrades automatically upgrade software.

Alternative services are systematically generated by adding conditions for the execution of services defined in Table 5.4. In Table 5.5, the condition of such a service is represented by a set of symbols of the conditions defined in Table 5.4. For instance, computer upgrades are performed when new functions are available "and" maintenance of the product is necessary. The condition of service is (Cn, Pf).

ISCL is equipped with an algorithm to find the following characteristics of the design alternative services. It is assumed that engineers are required for the services related with the product and computer. Some generated services with additional conditions are not unique (or not necessary), because other services in Table 5.4 bring the same or wider consequence under the same conditions ("NN"). For other service types, engineers become necessary to perform combined services ("ENG"). For instance, software upgrades do not originally require engineers, while computer upgrades combined with software upgrades require engineers. The remaining services in Table 5.5 are unique and they do not require engineers in addition ("OK"). Furthermore, these services is performed "in place of" or "an option with" other service in Table 5.4.

The characteristics of the alternative upgrading services with possible combination of the conditions are shown in Table 5.5. Eight alternative services are considered as feasible (i.e. "OK"). However, this example focuses on the evaluation of alternatives of the services with the computer described in Table 5.6. The exclusion of alternative designs for the quantitative simulation does not lose the generality of *ISCL*.

Table 5.4 Conditions and consequences of services

service type	conditions	consequences
Product replacement	Pn	Pn, Pf, Cn, Cf, Sn, Sf
Computer upgrade	Cn	Cn, Cf, Sn, Sf
Software upgrade	Sn	Sn, Sf,
Product maintenance	Pf	Pf
Computer maintenance	Cf	Cf
Software maintenance	Sf	Sf

Pn: Product newness, Cn: Computer newness, Sn: Software newness
Pf: Product function, Cf: Computer function, Sf: Software function

Table 5.5 Characteristics of alternative services

Product replacement with extended conditions		Computer replacement with extended conditions		Software replacement with extended conditions	
conditions	characteristics	conditions	characteristics	conditions	characteristics
(Pn, Pf)	OK	(Cn, Pn)	NN	(Sn, Pn)	NN
(Pn, Cn)	OK	(Cn, Pf)	OK	(Sn, Pf)	OK
(Pn, Cf)	OK	(Cn, Cf)	OK	(Sn, Cn)	NN
(Pn, Sn)	ENG	(Cn, Sn)	ENG	(Sn, Cf)	OK
(Pn, Sf)	ENG	(Cn, Sf)	ENG	(Sn, Sf)	OK

For instance, (Pn, Pf) stands for product replacement (Pn) performed at product function obsolescence (Pf)
OK: Feasible service, ENG: Not feasible because engineers become necessary, NN: Not necessary.

Table 5.6 Service alternatives for quantitative evaluation

type	symbol	interpretation
I-Type	Cn	Computer upgrading service independent from the physical deterioration of the computer and that of the entire product
C-Type	(Cn, Cf)	Computer upgrading service “in place of” the computer maintenance occurred due to too frequent failures or a fatal failure.
P-Type	(Cn, Pf)	Computer upgrading service as “an option with” the product maintenance due to the mechanical failures.

Modeling quantitative and probabilistic information

After generating alternative PSSs, the performances of the alternatives are quantitatively evaluated using a life cycle simulator (LCS). Additional quantitative parameters such as failure behaviors, the preference of users to the service types, interval of new function releases of the computer, market size and simulation durations are defined as follows.

- Stochastic failure behaviors are represented by rate of failure occurrence with respect to physical lifetime. The behaviors have a random phase, in which the occurrence is once per year on average, and a deterioration phase, in which the failure occurrence proportionally increases with respect to physical life time. The point of this phase shift depends on the type of product components (5 years for computers, 10 years for mechanical parts).
- The preference of users to each service is represented by the proportion of users, who choose the service when it is available. For instance, “80% to I-type” means that 80% of the users replaces (upgrades) the computers embedded in the product at the release of new computers.
- Interval of function releases of the rapid life cycle is 2 years, and that of the slow life cycle is 4 years.
- Market size: 100 Units

- Duration of a simulation: 30 years in simulation time, or 360 simulation steps.

Furthermore, *newness* (of functions of the embedded computers) is defined as a measurable value for evaluating the impact of functional upgrading service on life cycle cost defined shortly. A new product is equipped with new computer (*newness*=1), and the function deteriorates (*newness* increments) at the release of a new computer model with better functions.

In order calculate the life cycle cost (*LCC*) in this example, manufacturing cost, costs of the non-computer parts and the computer, and upgrade cost of the computer maintenance (c_p, c_m, c_{mc}, and c_{uc}, respectively) are defined in terms of the rate to the manufacturing cost as follows.

$$c_m = 0.01 \cdot c_p, \quad c_{mc} = 0.001 \cdot c_p, \quad c_{uc} = 0.002 \cdot c_p \tag{5.1}$$

Furthermore, it is assumed that maintenance costs of obsolete computers are higher than those of new computers due to storage costs for old components and/or software costs. Variation of such maintenance costs are described as a function of *newness* of the computer as follows.

$$c_{mc}(newness) = newness \cdot c_{mc} \tag{5.2}$$

P-type upgrades may save logistic costs of the service, because it is performed together with maintenance of the product. This is expressed as a rate of the upgrade cost of P-type relative to that of C- and I-types. Although, it is difficult to preliminary determine the rate at the design phase, this case study assumes as a target value.

$$c_{uc}(P) = 0.25 \cdot c_{uc}(C, I) = 0.25 \cdot c_{uc} \tag{5.3}$$

Using the above parameters as inputs, LCS simulates states of individual products in the market (e.g., *newness*, elapsed lifetime, functionality) and its transitions by instantiating activities. After the simulation, the cumulative numbers of the activities, whose costs have been defined above, are obtained as the indicators (N_p, N_m, N_{mc}, and N_{uc}).

Finally, the life cycle cost (*LCC*) is calculated using the results of a simulation. It is derived from the cumulative number of activities (*N*) and specific costs of the respective activities (*c*) as follows.

$$LCC = \sum c_i \cdot N_i, i \in (p, m, mc, uc) \tag{5.4}$$

Having defined the inputs and outputs of LCS, the goal of the analysis is to identify appropriate functional upgrading service (P-, C-, and I-type) for computers in computer-embedded systems, which minimizes the LCC under the various technology and market conditions. Figure 5.7 shows a screen hardcopy of *ISCL* during the definition and evaluation of the PSS.

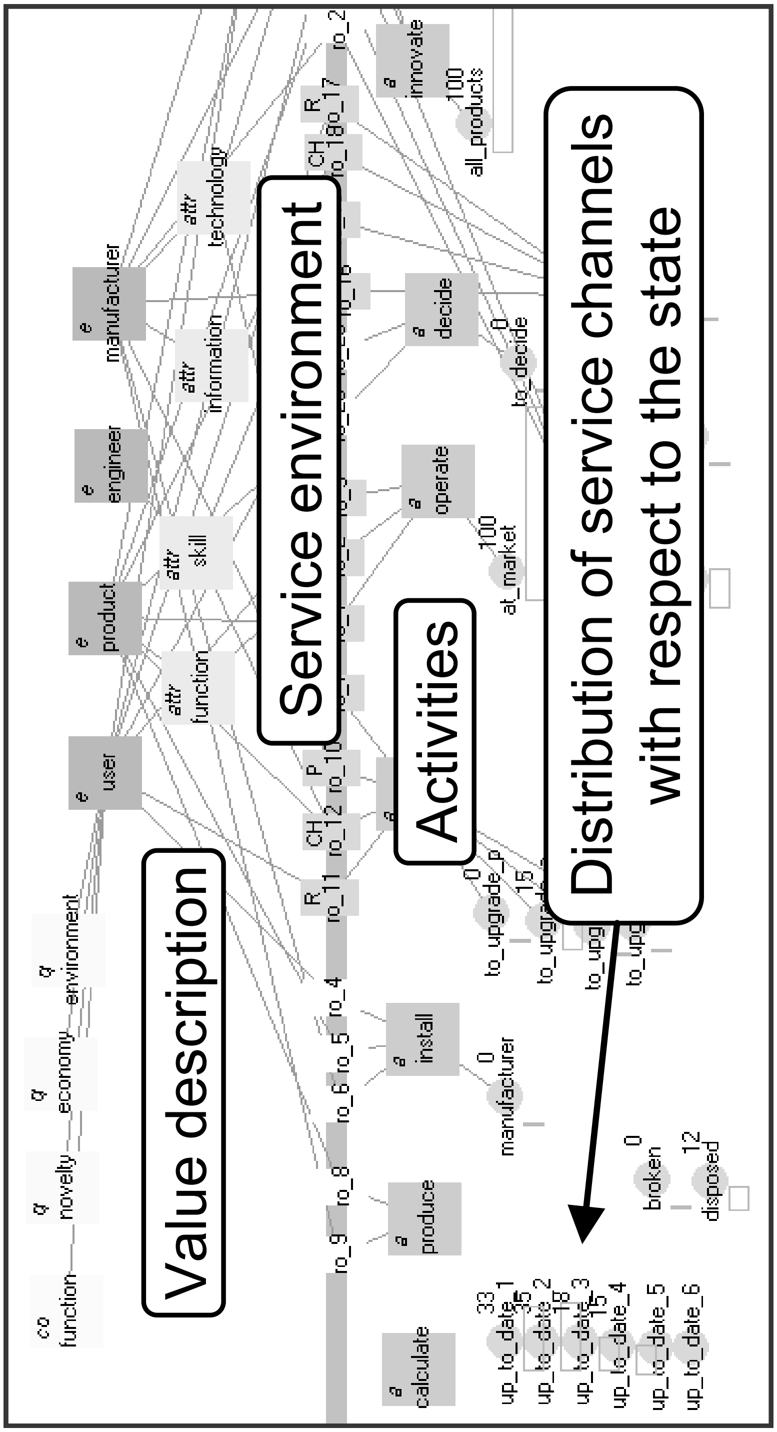

Fig. 5.7 Screenshot of *ISCL* displaying a life cycle simulation of a PSS model

5.3.2 Results and analysis

Table 5.7 shows the resulting cumulative number of activities with respect to the service types (in Table 5.6) and rate of the preferences to the service at different function release intervals (R: rapid and S: slow). A division of the number of the maintenance activities of the computer is made with respect to *newness* of the computer at the maintenance. Figs. 5.8 and 5.9 show the life cycle costs (LCC) normalized with the manufacturing cost. This becomes the basis to calculate TCO. The total manufacturing costs, which are almost 90% of the LCC, are not shown, because the results do not show significant deviation in the number of manufactured products among the simulations.

I-type upgrades decrease the maintenance costs of the computer by reducing the number of maintenance activities of functionally obsolete computers, while increasing that of new computers. In spite of the reduction, the LCC significantly increase due to increased upgrading activities. The more users prefer to this service and the quicker the function releases are, the higher become the eventual LCC. Nevertheless, this service can be economically feasible for a product with the computer parts, which become expensive or unavailable in the market (e.g. due to introduction of new OS or interfaces).

C-type upgrades decrease the maintenance costs of the computers by replacing the maintenance activities with the upgrading activities. Unlike I-type upgrades, they do not change the distribution of the newness of the computers in the market significantly, since upgrading activities depend on the failure occurrences of the computers. This means that the service is appropriate for a product with the computer parts, whose unit maintenance costs are independent of their functional obsolescence (e.g., servers with labor intensive maintenance). For instance, under the given cost rates in the case study, this type shows the best LCC performance among all upgrading service types.

P-type upgrades decrease upgrading costs by combining the service with maintenance activities of the product. Since this service depends on physical deterioration of the product (rather the computer), identification of concrete types of the computer parts suitable to this service is not trivial. However, in general, the service is appropriate for the computers with high maintenance costs.

In summary, to obtain better LCC, it is not advisable to upgrade computers at the occasion of product maintenance, but to run separately product upgrades and computer upgrades, only when computer upgrades are necessary.

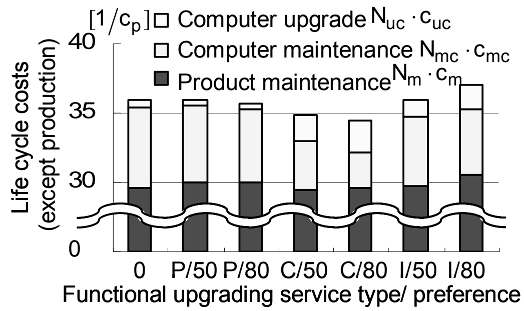

Fig. 5.8 Comparisons of the life cycle costs (rapid)

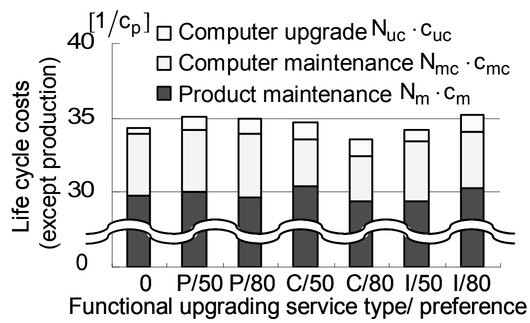

Fig. 5.9 Comparisons of the life cycle costs (slow)

Table 5.7 Simulation results

life cycle type	customer type	N_p	N_m	N_{mc} (1,2,3,4)	N_{uc}
rapid	0	300	2.959	2,785(691,1220,829,45)	249
rapid	P/50	299	3.006	3,248(1442,1397,400,9)	776
rapid	P/80	300	2.998	3,395(1782,1330,280,3)	914
rapid	C/50	300	2.940	2,572(1702,707,162,1)	912
rapid	C/80	300	2.958	2,352(2106,228,18,0)	1.144
rapid	I/50	300	2.970	3,187(1688,1176,314,9)	644
rapid	I/80	300	3.052	3,419(2337,896,182,4)	912
slow	0	300	2.984	2,704(1388,1273,43,0)	239
slow	P/50	300	3.010	3,115(2181,927,7,0)	477
slow	P/80	300	2.964	3,449(2624,825,0)	548
slow	C/50	300	3.048	2,772(2308,411,3,0)	524
slow	C/80	299	2.946	2,832(2716,116,0,0)	589
slow	I/50	300	2.947	2,985(2090,892,13,0)	437
slow	I/80	300	3.025	3,336(2856,478,2,0)	546

5.4 Designing total maintenance service package

Maintenance, which is crucial in the life cycle of such durable goods as computers, cars, and office equipments and such capital goods as machine tools and industrial robots, is widely varied, including occasional or regular module repair and spare parts and consumables supply. Its providers also vary from manufacturers to authorized or unauthorized third-party providers. Unless service quality varies significantly and added value is obvious to users, price-based maintenance competition may be severe.

To increase service competitiveness and users benefit in total ownership cost and convenience, manufacturers offer comprehensive service packages. For instance, some car and computer manufacturers offer all-in-one packages such as Mercedes Care (a trademark of Daimler AG.) and AppleCare (a trademark of Apple Inc.) These are useful in maintaining product value during the life cycle, especially when they give users optional tradeins to manufacturers or third-party dealers and are used by other users in the life cycle. Functional upgrades may also be built into service packages to meet performance-conscious user expectations.

Service packages may be difficult to design, however, for three reasons. First, content must be carefully determined considering competitors' offerings. Second, price must be competitive with competitors' discounts. Third, appropriateness to different users with specific preferences must suit service content and timing.

In using ISCL to analyze sales of manufacturers and third-party competitors while considering different user behavior and discount conditions in a product life cycle, the feasibility of comprehensive service packages for manufacturers is evaluated by calculating acceptable simulation-based package price range.

In this subsection, a LCS model to analyze service in a life cycle of durable and capital goods is shown (Section 5.4.2).After that, life cycle simulations based on the LCS model are conducted using ISCL (Section 5.4.3). In Scetion 5.4.4, the simulation results are analyzed regarding the feasibility of service under different user behavior and the competitor's discount, and the design of a maintenance service package.

5.4.2 Modeling user behaviors and competitions

As stated in Section 2.1, LCS has been used in designing business models taking into account product reuse, remanufacturing, and functional upgrading. We focused on designing maintenance services to be integrated in such business models using LCS. In the sections that follow an LCS model for service design in a product life cycle is introduced. The LCS model includes users and competitors to describe price-based competition.

Product model

Products consist of sets of modules, each module having physical and functional states and a failure rate for the elapsed lifetime. The physical state represents module functionality, i.e., functional or failure, and the functional state represents the function's newness – current or obsolete. These states change when the process model is activated as discussed below.

Process model

In the overview of process models in the LCS model we studied (Figure 5.10), new products are first produced in the production process, with the number of products determined by market demand. A regularly activated use process simulates product use in the life cycle. Some product modules will malfunction during the life cycle, and physical deterioration is a stochastic function of the module's failure rate. The function release process is activated based on predefined module function release plans because new module functions are released independently of product production and use. Activation causes a new module function to be released, making existing modules as part of market products obsolete. The decision on service selection among alternatives is triggered for individual products in the market when at least one module is broken or functionally obsolete. The process first identifies combinations of repair and upgrade for all product modules, then an identified combination is chosen for execution. Selection depends on the user type introduced shortly. If the service is provided by more than one service provider, that provider offering the cheapest price for the service is chosen. If no repair and/or upgrade service is available, products are removed from the market and new products introduced.

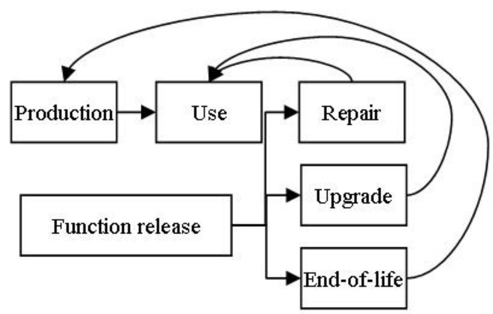

Fig. 5.10 Process model

User types

User types define how users select a service offering among alternatives from market service providers. The four user types we propose -- minimalist, opportunist, impulse buyer, and maniac -- differ in identifying modules to be repaired or upgraded and in determining repair and upgrade purchase timing (Table 5.8).

Minimalists, for example, are not interested in functionally upgrading purchased products, so sales to minimalists rest on product purchase and module repair. Opportunists purchase functional upgrades when modules break and functional upgrades are available for repair. Impulse buyers similarly consider module malfunctions as chances to purchase functional upgrades, but purchase all available functional upgrades when a module malfunctions, regardless of broken module upgradability. Maniacs purchase functional upgrades whenever they are available, considering that releases of new functionalities are chances to purchase functional upgrades independently of maintenance.

Table 5.8 Identifying modules for repair and upgrade by user

User	Repair	Upgrade
minimalist	Modules broken	No upgrade
opportunist	Modules broken and not upgradable	Modules broken and upgradable
impulse buyer		One module broken and modules upgradable
maniac		Modules upgradable

Competitions

Users selecting a service offering also select a service provider. The two service providers we introduce -- a manufacturer and a third-party competitor – compete in terms of service price. Each module has a unique repair and upgrade price. The repair price increases for functionally obsolete modules. Regarding price-based competition, it is assumed, first, that the price of a combined service offering is the sum of prices of individual service offerings. Second, the price of a specific service by a service provider is given as infinite in order to indicate that the service provider cannot deliver the service. Third, for service offering unavailability by all service providers, the combined service offering content are randomly broken down into two service offerings until service offerings become available from at least one service provider.

Life cycle simulation

The objective of this example was to evaluate the utility of life cycle simulation in analyzing the progress of sales by the manufacturer and by the third-party competitor during the product life cycle. The sales share distribution between the manufacturer and third-party competitor and estimated comprehensive service package price ranges for the manufacturer have been analyzed, while considering different user behavior and discount conditions of product life cycle services during analysis and evaluation.

Simulation setup

ISCL simulates car market behavior for 500 weeks (simulation times). Market demand is set at 100 and remains unchanged during one simulation. Our simplified car model consists of 12 reparable and/or replaceable modules and consumables classified into body parts such as doors, mechanical parts such as transmissions, exteriors such as side mirrors, electrical parts such as autoparking systems with integrated sensors, and consumables such as engine lubricant (Table 5.9). Modules have a failure rate r, a functional upgrade interval d, and prices for repair and functional upgrades. Repair for functionally obsolete modules are 50% higher than for repair for new modules, and these prices, which remain unchanged during a simulation, are used as the initial service price for both manufacturer and competitor. Only the manufacturer upgrades exteriors and electrical parts and repairs mechanical parts.

We conducted 20 simulations for each user with discounts for a set of the services specified in a discount situation and five types of price discounts for the above service by the competitor (Table 5.10).

The life cycle model developed on *ISCL* includes the product model, process model, performance indicators such as competitor and manufacturer sales, and subprocess model activation results including financial flows and physical and functional state transitions (Fig. 5.11). Quantitative and stochastic process and product model behavior are programmed using the editor. Simulation progress is checked using the simulation monitor.

Table 5.9 Module parameters

	r [1/week]	*d* [weeks]	repair [Euro]	upgrade [Euro]
body pars A	0.002	-	1,000	-
body pars B	0.002	-	2,000	-
body part C	0.002	-	4,000	-
mechanical part D	0.00285	-	500	-
mechanical part E	0.00285	-	1,000	-
mechanical part F	0.00285	-	1,500	-
exterior G	0.002	200	500	1,000
exterior H	0.002	250	1,000	2,000
electric part I	0.004	75	200	400
electric part J	0.00333	150	500	1,000
consumable K	0.06	-	-	100
consumable L	0.02	-	-	200

Table 5.10 Simulation indices

		minimalist	opportunist	impulse buyer	maniac
price discounts	*0*	1	2	3	4
by competitor	*body part (20)*	5	6	7	8
(%)	*exterior (20)*	9	10	11	12
	electric part (20)	13	14	15	16
	consumable (20)	17	18	19	20

5.4.2 Results and analysis

Simulation results

Total sales progress of the manufacturer and competitor for each user (simulations 1 - 4) have been tracked (see Figure 5.12). For accumulated manufacturer and competitor sales calculated in each simulation (Figures 5.13), total sales at use phase *P* are divided into sales for repair by competitor P_c and repair and upgrading by manufacturer P_m (Table 5.11).

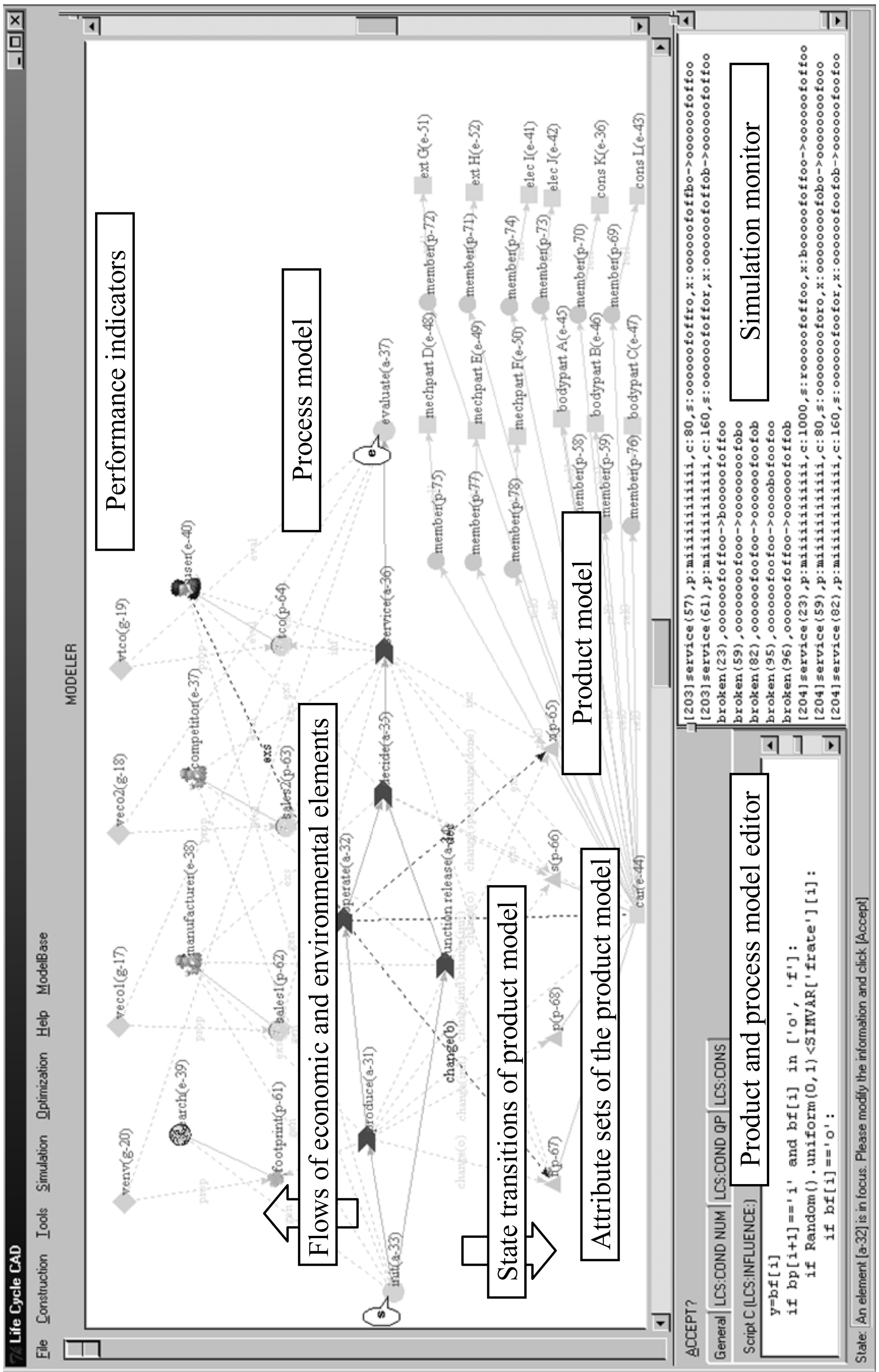

Fig. 5.11 A screen shot of LCS model on *ISCL*

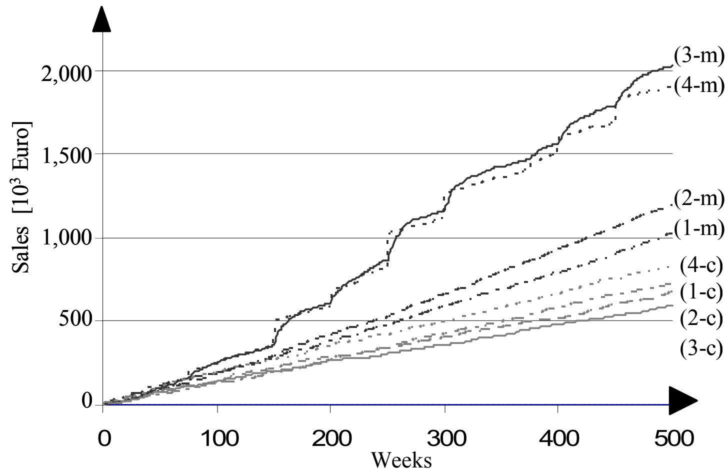

Fig. 5.12 Sales progress between a manufacturer and competitor based on four types of users -- 1-4: simulation indices; m: manufacturer; c: competitor.

Table 5.11 Accumulated sales by division [Euro 10^3]

index	P_m	P_c	*P*	*index*	P_m	P_c	*P*
1	1,025	722	1,746	11	1,964	593	2,557
2	1,187	669	1,856	12	1,775	735	2,510
3	2,024	595	2,619	13	911	799	1,711
4	1,899	830	2,729	14	1,173	653	1,825
5	689	1,006	1,695	15	2,008	639	2,647
6	838	819	1,657	16	1,878	801	2,679
7	1,733	826	2,559	17	796	999	1,796
8	1,608	891	2,498	18	907	914	1,821
9	955	824	1,778	19	1,829	703	2,532
10	1,155	672	1,828	20	1,641	866	2,507

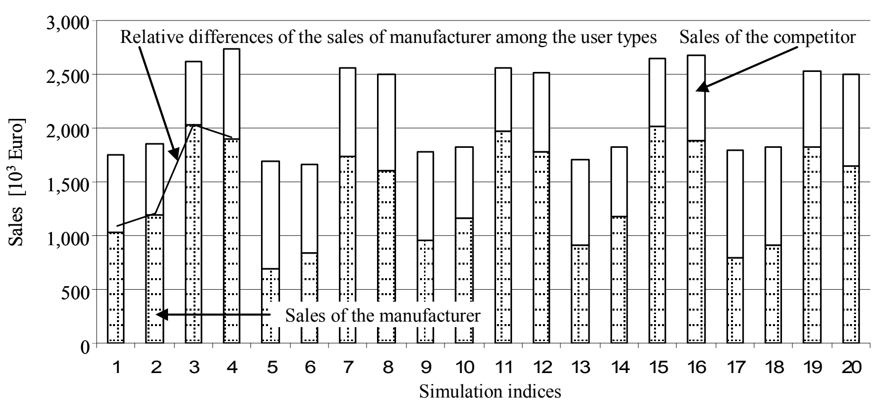

Fig. 5.13 Simulation results

Sales progress by user types

Sales of the manufacturer are higher than those of competitors for all users because the manufacturer can provide repair and upgrading not possible by competitors (see Fig. 5.12). The influence of the manufacturer's domination of mechanical parts repair on manufacturer and competitor sales shares is reflected in simulation 1 results.

Manufacturer sales increase with the number of upgrades, but the rate of increase depends on the type of user. Simulation 3, for example, shows a higher increase in manufacturer sales because users -- *impulse buyers* in this case -- purchase consumables whenever mechanical parts are repaired, a service only the manufacturer provides. Simulation 4 users -- *maniacs* -- in contrast, purchase consumables randomly from the manufacturer or competitor and ask the manufacturer separately to repair mechanical parts. In short, users' selection in service content and timing influences the distribution of sales shares in a competitive environment.

Competitor price discount influence on manufacturer sales

The competitor's service price discounts especially decrease the manufacturer's sales, although total sales for both decreases due to discounts.

Relative differences in manufacturer sales are maintained among users for all discount patterns, but the degree of decrease depends on the module type, for which prices are discounted. The manufacturer may, for example, maintain sales even when heavily discounting exterior repairs and electrical parts repairs, but the decrease in sales becomes significant if body parts repairs and consumables supplies are heavily discounted.

These differences occur because of how some nondiscounted services make other discounted services unnecessary. For nondiscounted services, the functional upgrading of exterior and electrical parts replaces repair services. No services replace body parts repairs or consumables supplies for discounted services.

Estimated service package price range

Manufacturers often provide comprehensive contract-based service packages to users in addition to on-the-spot services in crucial physical failures or new function release. A service package may, in principle, include any maintenance or functional upgrade in the product life cycle, so such a service must be designed carefully. We therefore estimated price ranges for such service packages in different price-based competition using life cycle simulation results.

Two service packages -- one including module repair and consumables supply (repair package) and the other further including the upgrading of exteriors and electrical parts (upgrade package) have been considered.

Package price ranges based on three assumptions have been estimated: First, the manufacturer's profit with a service package is better than that based on on-the-spot service. Second, the manufacturer must offer services included in a service package to users with contracts whenever the service is necessary or available -- this is needed to estimate maximum cost for the manufacturer by introducing the service package and also implies that user behavior from the manufacturer's perspective is simplified by introducing the service package. Third, manufacturer sales with a service package are lower than the manufacturer's and the competitor's total sales combined, i.e., total cost of ownership for users, without introducing the service package, an assumption required to estimate the maximum acceptable service package price charged to users.

Given these assumptions, the price range of service package *p* is formulated as follows:

$$\frac{r}{n}\{(1-\alpha)P'_m + \alpha P_m\} \le p \le \frac{r}{n}(P_m + P_c) \qquad (5.5)$$

where α is the average profit margin of services included in the service package, P'_m is the potential maximum sales of the manufacturer during contract period P_m, P_c is combined manufacturer and competitor sales without introducing the service package during the same period, *r* is the ratio of the contract period to the simulation period, and *n* is the market size.

P'_m for the repair package and the upgrade package is calculated by adding P_m and P_c obtained from simulation results 1, 5, 9,13, and 17 and 4, 8, 12,16, and 20. Results of the first set of simulations are based on the behavior of the *minimalist* and those of the latter on the behavior of the *maniac*. P'_m for calculating repair without considering price discounts, for example, is Euro 1,746,000 based on simulation 1, and P'_m for calculating upgrading without considering discounts is Euro 2,729,000 based on simulation 4 regardless of user type.

Repair and upgrade price ranges for *impulse buyers* under five different price discount conditions (Table 5.12) are determined with an average profit margin of service $\alpha = 0.16$ and a contract period of 50 weeks, or $r = 0.1$.

Ranges of both packages without discounts are smaller than with discounts. The width of the range with price discounts is due to the fact that the ratio of manufacturer sales to those of the competitor is high before the service package is introduced, meaning that the manufacturer is not competitive when the competitor offers services with discounts. Put another way, lower sales shares before the service package is introduced lower the minimum acceptable service package price for the manufacturer.

The narrowness of the estimated upgrade package range without discounts is because the service package is provided to *maniacs* and to *opportunists* and *impulse buyers*, who purchase fewer functional upgrading services than *maniacs*. This means that the total cost of ownership for these user types is lower than that of *maniacs* before the service package is introduced. To get these users as package customers, the manufacturer must lower the package price, meaning the maximum acceptable price.

Table 5.12 Acceptable service package price range [Euro 10^3]

types of discounts	repair package	upgrade package
0	1,630 - 1,746	2,615 - 2,619
body part (20)	1,533 - 1,694	2,375 - 2,558
exterior (20)	1,646 - 1,778	2,422 - 2,557
electric part (20)	1,582 - 1,710	2,571 - 2,646
consumable (20)	1,635 - 1,795	2,398 - 2,532

The upgrade package range is estimated for *impulse buyer*.

5.5 Conclusions

In this chapter *ISCL* has been applied to the analysis of service offerings in the life cycles of durable and capital goods. The service offerings in the case studies have included function sales, shared services, maintenance, functional upgrading, while considering uncertain user behavior, stochastic product physical deterioration, and price-based competitions. The design information to describe the service offerings under probabilistic service environment have been formally classified into the elements of the PSS model developed in Chapter 3, and the performance of life cycle models including them have been evaluated using the life cycle simulator presented in Chapter 4. The study in this chapter is concluded with the following remarks regarding the research questions.

Remarks related to the research question 1b

In the case studies in this chapter, various types of information have been considered as design parameters of business models. The types have included attributes of products, conditions and consequences of services, and behavior of users to select the services. The simulation results have shown that the performance of business models can be improved without changing (attribute values of) products. This indicates that the service can be adjusted in order to optimize the performances after the fixation of product design at an early design stage.

The case studies have also shown that the performance in individual service offerings is determined in relation with other service offerings. In other words, design information that relates individual service offerings one another is crucial to improve the performance of business models from a systemic perspective. Considering some critics about contribution of the PSS concept to system level innovation (Williams 2007), utilization of this information is a premise of PSS design.

Remarks related to the research question 2a

The second case study has shown that *ISCL* can handle questions like, to accommodate new functions, whether to change the computer hardware considering future maintenance costs or to upgrade only software. This is because of that the tool can explicitly consider the information among the service offerings in a product life cycle as described above. Similarly the last case study has demonstrated that *ISCL* is also useful in designing packages of service offerings considering such relations. Especially, the package design has been efficiently supported by selecting some possible design alternatives using qualitative design information defined by the designer, and evaluating the selected design alternatives using quantitative and probabilistic information by means of life cycle simulation. Further research is necessary to find appropriate qualitative design information for the selection procedure.

The case studies in this chapter have been restricted in terms of the scope of products and services included in a business model. For instance, the conditions of service offerings are described in terms of the state of a product at individual customer's hand, and the state of service environment (e.g., available alternative products and service offerings by competitors). However, states of other products and services in their own life cycles have not been explicitly considered as the execution conditions of service offerings. Further research is therefore necessary to find business models in practice that integrate the information about life cycles of diverse types of products, and to computationally support comprehensive design of service offerings in such business models.

Remarks related to the research question 2b

Although the study in this chapter has not provided new arguments regarding organization and utilization of PSS design information on top of the remarks presented in the previous chapters, an increase of the types of products and services to constitute a business model inevitably requires both the experts in specific product and service domains and the designers to relate the information about these products and services.

6 Considering other operations in product life cycles

In the previous chapter, *ISCL* has been applied to the analysis of service offerings in the life cycles of products. In comparison with the previous chapter, the focus of this chapter is on the analysis of supply chains of OEMs (original equipment manufacturers). Operations in the supply chains are not visible from the customers, although these operations influence the performances of OEM from a life cycle perspective. These operations can be related with end-of-life operations of OEMs and they are jointly considered as necessary elements of industrial product service systems (Transregio29 2008). In this chapter, a method to analyze the capability of OEMs to reconfigure their supply chain and end-of-life operations to achieve performance targets is proposed. The targets are defined in terms of environmental impacts and life cycle costs. Using life cycle simulation (LCS) on *ISCL*, the physical deterioration and the functional obsolescence of individual products are considered as stochastic elements in the analysis. A potential usage of the proposed method is the design of long-term relationships between OEMs and stakeholders in their supply chain and end-of-life process, while considering uncertainty in future environmental legislation changes. The analyzed capability of reconfiguration of these operations represents partially of the robustness of OEMs against uncertainty from a life cycle perspective.

6.1 Introduction

Original equipment manufacturers (OEMs) often need reconfiguration of their supply chain to follow environmental legislations such as the Directive on Waste Electrical and Electronic Equipment (WEEE 2002) and the Restriction of Hazardous Substances Directive (RoHS 2002). The reconfiguration at an operational level consists mainly of reallocation of component orders to OEM suppliers, which have been designed to optimize multiple performance criteria such as cost, delivery time, delivery performance (reliability), and quality (Wang et al. 2004). From a life cycle perspective, OEMs can reduce life cycle costs and environmental impacts (e.g., resource consumption, emission) by designing end-of-life operations to improve the logistics of used products and components (Umeda et al. 2000). In this chapter, a method to evaluate the capability of an OEM to reconfigure its supply chain and end-of-life operations to achieve a performance target is proposed. The target is quantitatively described with environmental impacts and life cycle costs.

The aforementioned reconfiguration capability is crucial for OEMs to adapt themselves not only to environmental legislations, but also to strategic policies initiated by OEMs themselves. These policies are, for instance, based on the principle of Extended Producer Responsibility (EPR). These policies are initiated in order to attract customers from an environmental perspective by differentiating themselves from competitors (Tojo 2004). In either case, these legislations and policies include quantitative target descriptions (e.g., reduction of resource consumption by 20% in five years). Quantitative information in these descriptions is often uncertain when OEMs design their supply chain and end-of-life operations. Thus, the above capability partially represents robustness of OEMs against introductions and changes of these legislations and policies with a certain degree of uncertainty.

For the evaluation of the reconfiguration capability presented above, various stochastic elements in a life cycle have to be considered. Besides demand fluctuation of products in a market, physical deterioration and functional obsolescence of products in a life cycle are considered as stochastic phenomena in this study. These phenomena influence the number of used products and components collected by OEMs. They also influence the operations of OEMs that control the logistics of new and used products and components.

The majority of the reviewed methods in Section 2.1.3 and Section 2.1.4 do not explicitly define such stochastic phenomena of individual products as physical deterioration in their supply chain models. This is why these methods cannot support the decision making of OEMs regarding supply chain and end-of life operations considering such stochastic phenomena. The life cycle models reviewed in Section 2.1.2 deal explicitly with these stochastic phenomena as state transitions of individual products. LCS is based on these models and it supports quantitative performance evaluation of life cycles. In the simulation procedure, the dependency of end-of-life operations on the state of individual products is considered. However, the focus of the studies using LCS is on the analysis of end-of-life operations. This is why LCS has not been used to support the decision making of OEMs regarding their supply chain operations. For OEMs, modeling of their supply chain operations integrated with their end-of-life operations indicates that OEMs can improve their performance by reconfiguring both types of operations considering their interrelations. The integrated model can be particularly useful in evaluating the capability of an OEM's supply chain and end-of-life operations to achieving a performance target.

The study presented in this chapter is an extension of the previous studies by the author. In these studies, a method to evaluate the performances of an OEM's supply chain in terms of multiple criteria (costs, environmental impacts, delivery performance) using discrete event simulation has been proposed (Nagel et al. 2005). Furthermore, a method for an OEM to optimize its supply chain operations subject to the above performance criteria using a multi-objective genetic algorithm has been proposed (Komoto et al. 2005). In this chapter, LCS is used to evaluate the performances of an OEM's supply chain operations considering end-of-life operations in terms of the above performance criteria. The optimized results of LCS indicate the performance of the OEM that can be achieved by reconfiguring these operations.

This chapter is organized as follows. In Section 6.2, a LCS model including supply chain operations, the simulation, optimization, and reconfigurability evaluation procedure, are described. In Section 6.3, a case is introduced to demonstrate the proposed method. The objective of this case is to evaluate whether an OEM can obtain some economic and environmental performance targets with its current supply chain and end-of-life operations. The case is followed by analysis about the case in Section 6.4, and discussions about the applicability of the method to industrial practice and its limitation in general in Section 6.5. In Section 6.6, this chapter is concluded.

6.2 Method

In this section, a method for OEMs to model, simulate, and optimize their supply chain and end-of-life operations is described. The proposed method supports evaluation of the capability for OEMs to achieve performance targets. In this study, the targets are quantitatively described with environmental impacts and life cycle costs. Other performance indicators (e.g., delivery performance) can be considered as the targets. First, a life cycle model for LCS used in this study is briefly described (Section 6.2.1). Second, supply chain operations in the life cycle model to select and prioritize suppliers considering the number of reusable products and components are formulated (Section 6.2.2). A technique for OEMs to evaluate the above capability using the life cycle model and supply chain formalization is described (Section 6.2.3).

6.2.1 Life cycle modeling

The life cycle model for LCS used in this study consists of product models and process network. In addition, performance indicators are defined for the evaluation of simulation results. Here a set of the assumptions in constructing the life cycle model is clarified. Other assumptions about the generic life cycle model for LCS are found in related work quoted in Section 2.1.2.

Product model

The product model used in this study is characterized by modularity, physical deterioration, and functional obsolescence.

- Modularity: A product consists of a set of components. A product and its components own the individual elapsed lifetime, whose initial value is 0.
- Physical deterioration is a stochastic phenomenon derived from the property of individual product components: To represent this phenomenon, each component owns a physical state and a probabilistic function for the transitions of the physical state. The physical state is either *healthy* (initial value) or *broken*. The probabilistic function is defined with respect to the elapsed lifetime and calculated by its failure rate (or reliability). The physical state transition of components from *healthy* to *broken* is caused by the product use event. The

physical state of a product is *broken* if the physical state of at least one of the components is *broken*, otherwise it is *healthy*.

- Functional obsolescence is a stochastic phenomenon derived from the perception about products by customers at individual market segments. To represent this phenomenon, each product owns a functional state and probabilistic functions for the transition of the functional state. The functional state is *new* (initial value) or *obsolete*. The state transition from *new* to *obsolete* is caused by the introduction of products with new functions into individual market segments. This is why each probabilistic function corresponds to one market segment.

Process network

The process network consists of a set of processes owned by an OEM, suppliers, and a market with several segments (Fig.6.1). These process periodically instantiate corresponding events during a life cycle simulation. At every simulation step, each process calculates the number of event instantiations and instantiates (executes) the events. The number of event instantiations depends on the state of individual products and other simulation states (e.g., elapsed simulation time). For instance, the product usage process instantiates events to cause the above physical state transition on the individual products, which are in the market. The physical state transition does not occur to the products stored at the OEM. Description of the other process follows the generic description about the process network in Umeda et al. (2000). Compared with the generic description, the process network in this study has extensions from the following aspects.

- *End-of-life operations:* Broken and obsolete products are collected from the market. Collected and obsolete products can be delivered to the other market segments. Collected and obsolete or collected and broken products are disassembled. The components (i.e., disassembled products) are used for the components of products delivered to the same or other market segments. If the components become so old that no market segments accept the components, they are disposed. The decisions included in the end-of-life operations are made not only based on the individual collected product and component states. They are bus also based on the demand from individual market segments and on the number of reusable products and components at the OEM.
- *Postponing the decisions at end-of-life operations:* The decisions in the end-of-life operations can be postponed until the usage of collected products and components becomes evident. For instance, collected and reusable products are firstly stored for product reuse. They are disassembled, when there is no demand for the products from all market segments.
- *Delay in component delivery:* In the process network, physical component delivery is separated from the component order placement. This separation is necessary to explicitly evaluate the delivery performance of suppliers as one of the critical evaluation factors (Wang et al. 2004). The delay is characterized by a probabilistic function of the intervals between a component order delivery from the OEM and the corresponding component delivery to the OEM. The component

delivery delay causes the corresponding product delivery delay to the market. The product delay is defined as one of the performance indicators as follows.

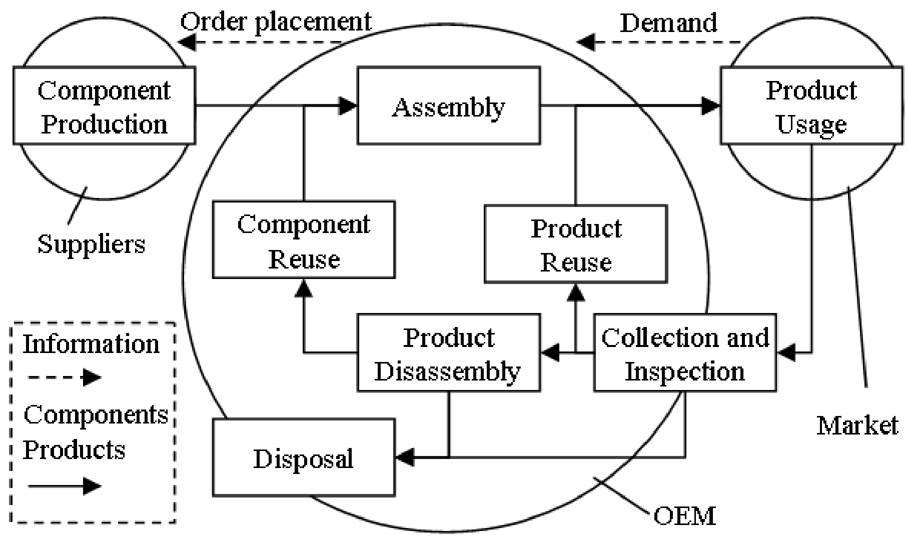

Fig. 6.1 Process network in a life cycle model

Performance indicators

In this study, three indicators (costs, environmental impacts, delivery performance) are introduced for the performance evaluation of simulation results.

- (Economic) costs are calculated by accumulating the cost generated at a single time interval over the entire simulation period. The cost generated at a single time interval is a sum of the costs for component delivery, product assembly, product delivery, product collection, collected product storage, and product disassembly.
- The calculation of environmental impacts is similar to that of the costs described above. It is calculated by replacing the costs with the corresponding environmental impacts.
- The rate of market fulfillment, which has been proposed as a performance indicator of a life cycle model (Kondoh et al. 2005), is used for the calculation of the delivery performance. The rate of market fulfillment at a single time interval is defined by the number of products delivered to the market within the interval relative to the number of products requested from the market for the same interval. The delivery performance is the average of the rate of market fulfillment over the entire simulation period.

6.2.2 Supply chain operations in LCS

The following procedure represents the supply chain operations focused in this study. This procedure is integrated with the above life cycle model. This procedure is executed at every time step during a life cycle simulation. The input of the procedure is the demand for products from individual market segments, and the output is component orders to individual suppliers. The variables and constants used in the procedure are summarized in Table 6.1.

Table 6.1 Nomenclature

Notation	
i	market segment i = 1,…,L
j	supplier j = 1,…,M
k	component k = 1,…,N
t	discrete time step t = 1,…, the simulation period of LCS
l	performance criterion l = 1,…,X (1=economy, 2=environment, 3=delivery)
Time dependent variables	
t_p	elapsed life time of individual products
t_c	elapsed life time of individual components
$d_i(t)$	demand for products form market segment i
$p(t)$	number of new products assembled at OEM
$pn(t)$	number of new products reserved at OEM
$pu_i(t)$	number of used products delivered to market segment i
$pu_i(t, t_p)$	number of used products with elapsed life time t_p delivered to market segment i
$pu(t, t_p)$	number of used products with elapsed life time t_p reserved at OEM
$c_k(t)$	number of components k to be purchased by OEM
$cn_k(t)$	number of new components k reserved at OEM
$cu_k(t)$	number of used components k reserved at OEM
$cu_k(t, t_c)$	number of used components k with elapsed life time t_c reserved at OEM
$c_{jk}(t)$	number of components k purchased from supplier j
Constants	
$\overline{c_{jk}}$	manufacturing capacity of component k at supplier j
Optimization variables defined by OEM	
$w^{(l)}$	weight of order placement to suppliers with respect to performance criterion l
rp_i	range of product elapsed life time allowed for redistribution into market segment i
rc_k	range of elapsed life time of component k allowed to reuse for remanufacture

First, the total number of products to be assembled $p(t)$ is calculated in Equation 6.1:

$$p(t) = \max[\sum_{i=1}^{L}(d_i(t) - pu_i(t)) - pn(t), 0] \tag{6.1}$$

where the number of *collected* and *healthy* products reused for a market segment $pu_i(t)$ is determined by the relation represented by Equation 6.2.

$$pu_i(t) = \sum_{t_p=0}^{\infty} pu_i(t,t_p) = \min[d_i(t), \sum_{t_p=\min(rp_i)}^{\max(rp_i)} (pu(t,t_p) - \sum_{i'=1}^{i-1} pu_{i'}(t,t_p))] \tag{6.2}$$

The OEM iteratively determines $pu_i(t)$ for all market segments following the priority assigned to the segments in distributing used products. The number $pu_i(t)$ for a specific market segment is calculated by adding the remaining reusable products reserved at the OEM with respect to the elapsed life time within the defined range until the sum reaches the demand for products at the market segment, or there are no remaining reusable products within the range.

Second, the total number of necessary components $c_k(t)$ is determined by Equation 6.3.

$$c_k(t) = \max[p(t) - cn_k(t) - cu_k(t), 0] \tag{6.3}$$

The OEM treats used components as *reusable*, when their elapsed lifetime is within the range defined by the OEM with respect to each component type. The number of reusable components $cu_k(t)$ is formulated in Equation 6.4.

$$cu_k(t) = \sum_{t_c=\min(rc_k)}^{\max(rc_k)} cu_k(t, t_c) \tag{6.4}$$

Equation 6.4 is based on the assumption that reusable components are used as components for new products. In other words, reusable components are mixed with new components. This assumption is appropriate in case that the remaining physical lifetime of components is independent of the functional obsolescence of products.

Third, the orders of components to suppliers are calculated from single evaluation criterion in Equation 6.5.

$$c_{jk}{}^{(l)}(t) = \min[c_k(t) - \sum_{j'=1}^{j-1} c_{j'k}{}^{(l)}(t), \overline{c_{jk}}] \tag{6.5}$$

In this step, the rank of suppliers during the order calculation should be defined with respect to each performance indicator (economy, environment, and delivery). They are determined by the parameter values of suppliers related with the indicators in Section 6.2.1.

Finally, the total number of component order to be placed to each supplier from multiple performance criteria is a weighted sum of the component orders calculated from each criterion.

$$c_{jk}(t) = \sum_{l=1}^{X} w^{(l)} \cdot c_{jk}{}^{(l)}(t) \tag{6.6}$$

$$\sum_{l=1}^{X} w^{(l)} = 1 \tag{6.7}$$

In this equation, w denotes a weight on the respective evaluation criterion. All weights are always positive in order to prohibit negative order size.

6.2.3 Reconfigurability analysis

Simulated performance of the life cycle model (Section 6.2.1), which includes the supply chain formulation (Section 6.2.2), depends on the value of parameters rp_i, rc_k and w in Equations 6.2, 6.4 and 6.6. In other words, the OEM can adjust the performance by changing these parameter values, while maintaining the other parameter values (e.g., component purchasing costs, product assembly costs) unchanged.

For the effective exploration of these parameter values, a multi-objective optimization algorithm is employed. In the optimization procedure, these parameters are treated as the optimization parameters, and the performance indicators are treated as the objective functions to be minimized (costs, and environmental impacts), or maximized (delivery performance). This approach is similar to the study in Hugo and Pistikopoulos (2005). In that study, an optimization technique was employed to identify trade-off performances of a process network from multiple perspectives. The present approach is different from that study in that the present approach considers end-of-life operations and stochastic behavior of individual products in order to evaluate the performance of OEMs. An optimization program implemented on ISCL was based on the multi-objective genetic algorithm developed by Fonseca and Flemming (1993).

In Fig. 6.2, the life cycle model developed on ISCL is shown. A process network (center) and a product model (bottom right) are shown on the top window. Squares in the process network represent individual processes. Circles in the process network represent specific states of products or components. The number on the right top of these circles shows the number of products or components in the specified states. Presentation of these numbers is useful for the designers to observe the simulated behavior. Simulation results are displayed on the bottom window.

6.3 A case study

In this sub section, the proposed method is demonstrated using a case. The objective of this case is to evaluate the capability of an OEM to obtain performance targets in terms of environmental impacts (considering other performance indicators) with its current supply chain and end-of-life operations. In this case, the supply chain operations of the OEM studied is integrated with four different end-of-life scenarios. The supply chain and end-of-life operations are simulated and analyzed with respect to each end-of-life scenario. The end-of-life scenarios studied in the case are described as follows.

- Disposal scenario: Products are disposed immediately after the collection.
- Component reuse scenario: Products are immediately disassembled after the collection. The components (i.e., disassembled products) are reused for the product remanufacturing when they are healthy and their elapsed lifetime is within the defined range (of reusability) with respect to each component.
- Product reuse scenario: Broken products are disposed immediately after the collection. Healthy products are stored at the OEM's inventory after the collection. Healthy products are redistributed into a market segment, when there is demand for the products from the market segment and their elapsed lifetime is within the defined range with respect to the market segment.
- Component and product reuse scenario: This is a combined scenario of the component reuse scenario and the product reuse scenario. Healthy products are

stored at the OEM's inventory after the collection. Their redistribution into the market follows the rule described at the product reuse scenario. The stored products are disassembled when the products do not satisfy the redistribution conditions regarding all the market segments any more (see. Equation 6.2) and at least one of the components is reusable.

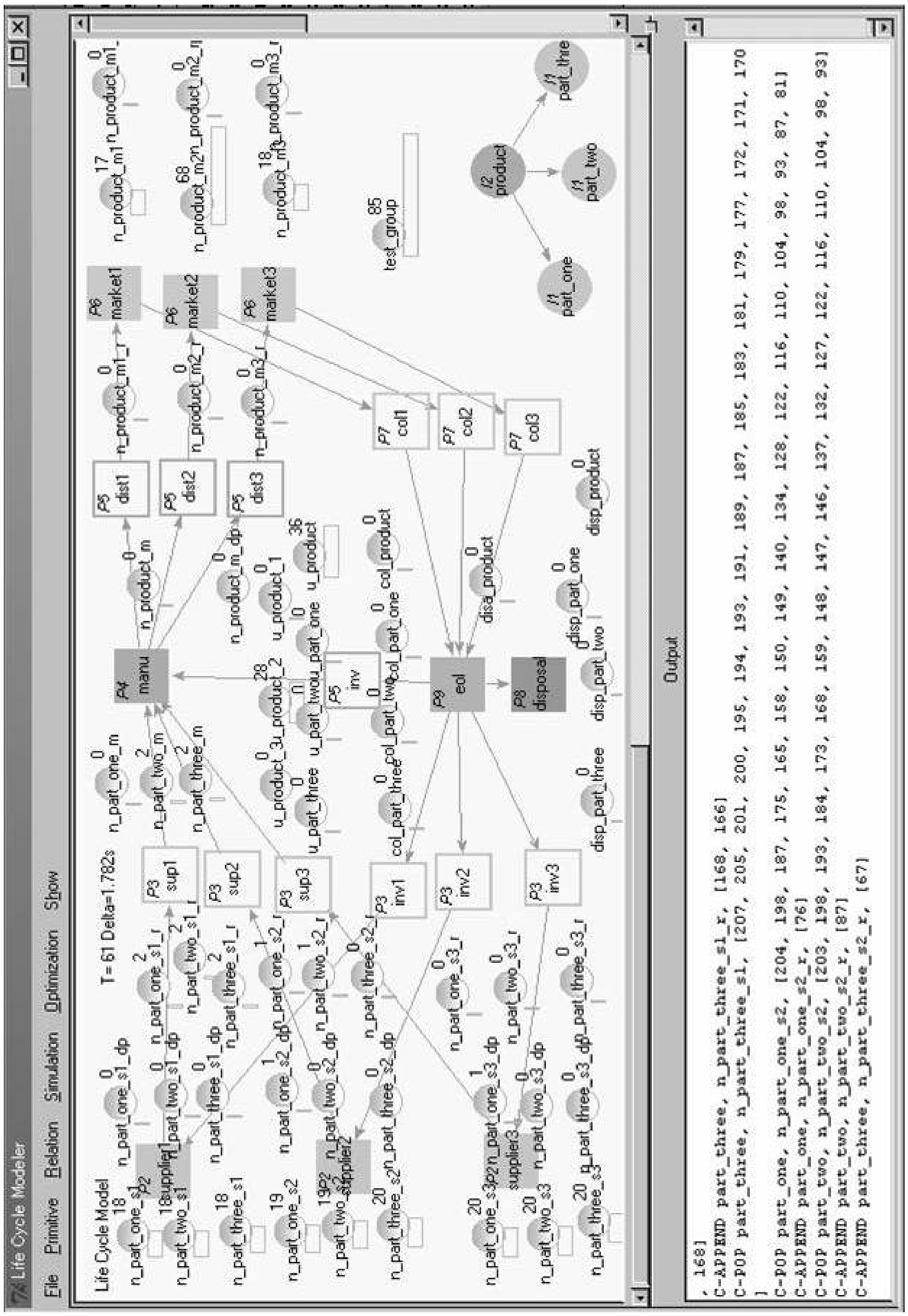

Fig. 6.2 A life cycle model developed on *ISCL*

6.3.1 Simulation setting

The product model consists of three components. Probability functions to characterize the physical deterioration of each component are shown in Fig.6.3. The process network consists of an OEM, three component suppliers, and three market segments. Their parameters are presented in Tables 6.2, 6.3 and 6.4, and explained as follows. Each supplier delivers all components with specific stochastic delay, costs, and environmental impacts. Each market segment (see. Table 6.3) is defined by the demand profile of products with a linear introduction phase and by a probability function to characterize their functional obsolescence (see. Fig. 6.4). An order of the market segments in calculating the number of product reuse (see Equation 6.2) is defined. The order is not assigned to a market segment, when the segment does not accept used products. The three suppliers are ordered from multi-objective perspectives. The orders are used in Equation 6.5. The orders are determined by their delivery performance in Table 6.3, and their economic and environmental performances at the component delivery in Table 6.4, respectively. Costs and environmental impacts at the OEM's processes (production, product delivery, end-of-life operations, and product storage) are also shown in Table 6.4.

The duration of a life cycle simulation is 150 weeks (1 week = 1 time step). This means that the evaluation of physical deterioration and functional obsolescence in Section 6.2.1, the supply chain operations in Section 6.2.2, and the operations specified by one of the end-of-life scenarios described at the introduction of this case study, are iteratively performed for 150 times. As a result of one simulation, the costs, environmental impacts, and delivery performances defined in Section 6.2.1 are calculated.

In Table 6.5, possible values of the optimization parameters with respect to each end-of-life scenario are shown. For the sake of simplicity, some of the variables are unchanged in this case. The default values are used for the life cycle simulations shown in Section 6.3.2.

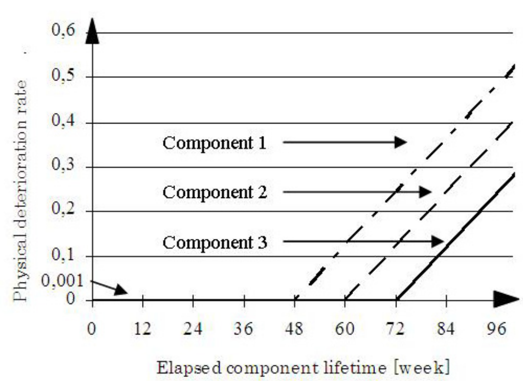

Fig. 6.3 Probability functions representing component physical deterioration

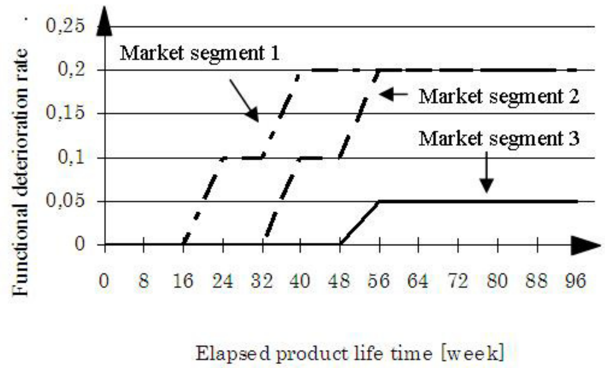

Fig. 6.4 Probability functions representing product functional obsolescence

Table 6.2 Market parameters

Market segment	i=1	i=2	i=3
Size [product unit]	18	72	18
Linear product introduction interval	[1,6]	[7,18]	[19,24]
Order of reusable product redistribution	Never	1	1

Table 6.3 Supplier parameters

Supplier	j=1	j=2	j=3
Component delivery delay (distribution function) [time units]	0 (97%) 1 (2%) 2 (1%)	0 (99%) 1 (1%) 2 (0%)	0 (99%) 1 (2%) 2 (0%)
Prioritization of suppliers from multi-objective perspectives (C: Economy E: Environment, D: Delivery)	C: 1 E: 3 D: 3	C: 2 E: 2 D: 1	C: 3 E: 1 D: 2

Table 6.4 Specific costs and environmental impacts

Process	Costs	Environmental impacts
Component delivery (supplier j=1)	1	4
Component delivery (supplier j=2)	2	2
Component delivery (supplier j=3)	4	1
Product assembly	3	3
Product delivery	2	2
Product collection	1	1
Product disassembly	1	1
Product storage at OEM's inventory	0.01	0.01

Table 6.5 Optimization parameters

Parameters	Possible values	Default value
w^1(economy)	w^1=[0, 1/15, 2/15, ...,1]	1
w^2(environment)	w^2=[0, 1/15, 2/15, ...,1]	0
w^3(delivery)	w^3=[0, 1/15, 2/15, ...,1]	0
rp_1	No remanufactured products to market segment 1	not defined
rp_2	$0 =< \max(rp_2) =< 40$	$\min(rp_2)=0$, $\max(rp_2)=40$
rp_3	$\max(rp_2)=\min(rp_3) =< \max(rp_3) =< 56$	$\min(rp_3)=40$, $\max(rp_3)=56$
rc_1	const.	$\min(rc_1)=0$, $\max(rc_1)=48$
rc_2	const.	$\min(rc_2)=0$, $\max(rc_2)=60$
rc_3	const.	$\min(rc_3)=0$, $\max(rc_3)=72$

6.3.2 Simulation results

Figures 6.5, 6.6, 6.7 and 6.8 show the result of a life cycle simulation with respect to each end-of-life scenario. Each figure shows the number of products at each market segment. In addition, Figs. 6.7 and 6,8 show the number of reusable products stored at the OEM. As shown in Fig.6.7, an excessive number of reusable products are stored at the OEM under the product reuse scenario. Such a high inventory causing additional storage costs can be resolved under the product and component reuse scenario (see Fig.6.8). Furthermore, the product flows can be optimized by adjusting the parameters specific to the end-of-life scenario in Table 6.5. However, further analysis of the product flows is out of the focus of this study.

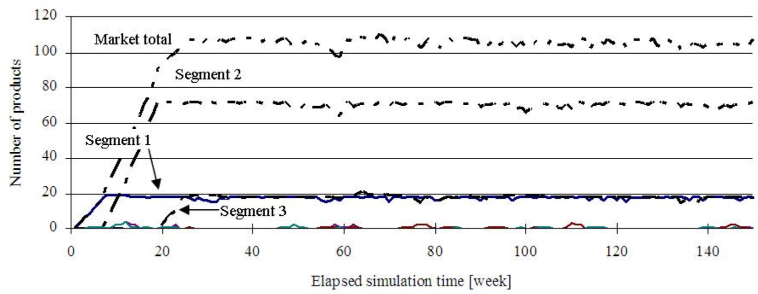

Fig 6.5 Simulation result of the disposal scenario

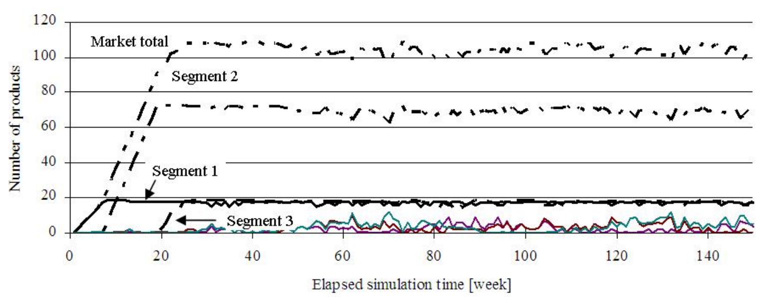

Fig 6.6 Simulation result of the component reuse scenario

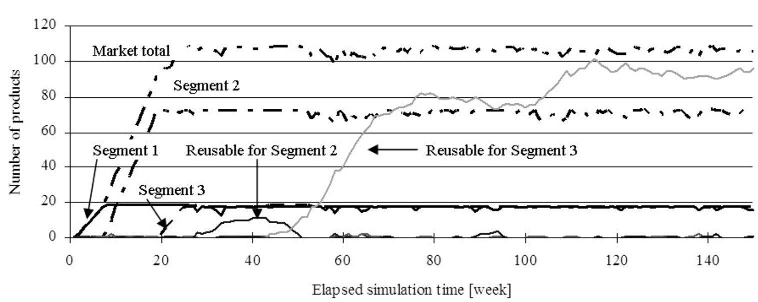

Fig. 6.7 Simulation result of the product reuse scenario

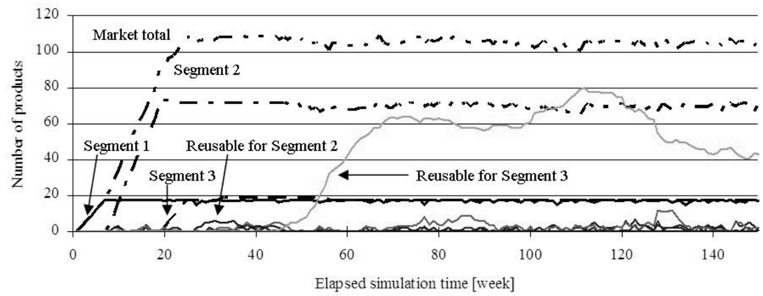

Fig 6.8 Simulation result of the component and product reuse scenario

6.3.3 Optimization results

Figures 6.9, 6.10 and 6.11 show the optimization results. For the visualization purpose, projections of the results with respect to the two selected performance indicators are presented. In these figures, a single plot represents the result of one life cycle simulation. Table 6.6 shows the number of obtained Pareto optimal performances, the average and standard deviation of these performances with respect to each scenario. Table 6.7 shows the correlations between the weights in the supply chain operations and the multi-objective performances. Table 6.8 shows the values of the selected Pareto optimal performances and the corresponding optimization parameter values for the analysis in Section 6.3.4.

As is shown in Table 6.6, the product reuse scenario gives the best result in terms of the average performance, while the component reuse scenario is inferior to the other three scenarios. It is interpreted from the resulting average performance that, first, supplier prioritization from multiple objectives alone (i.e., the disposal scenario) is insufficient for the performance optimization, when multiple life cycle scenarios are available. Second, product reuse is economically and environmentally efficient than component reuse for remanufacturing in the life cycle model. The simulation result indicates that the component reuse scenario can be improved by, for instance, (a) cost and environmental impact reduction at the disassembly process, (b) integrating the scenario with the product reuse scenario (i.e. the component and product reuse scenario) with appropriate parameter settings to optimize the intensity of disassembly operations. Although further investigation regarding the improvement of a specific end-of-life scenario by changing the corresponding parameter values can be of the interest for the research in life cycle simulation (see. Section 2.1.2), the focus of this study is on the reconfigurability analysis using the present optimization results.

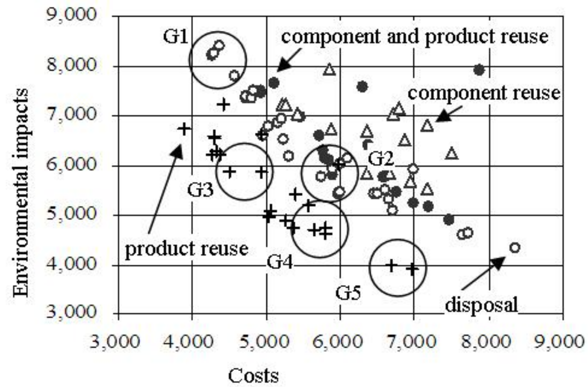

Fig.6.9 Optimization results (Costs vs. Environmental impacts)

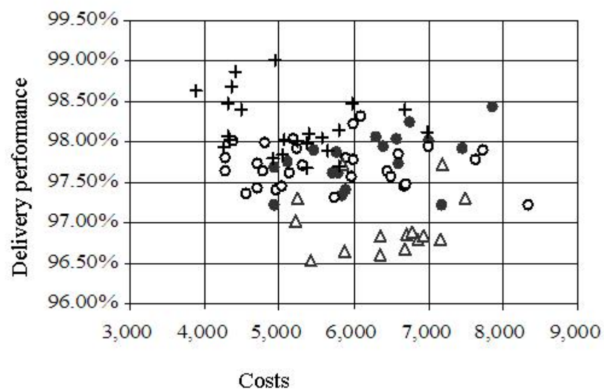

Fig. 6.10 Optimization results (Costs vs. Delivery performance)

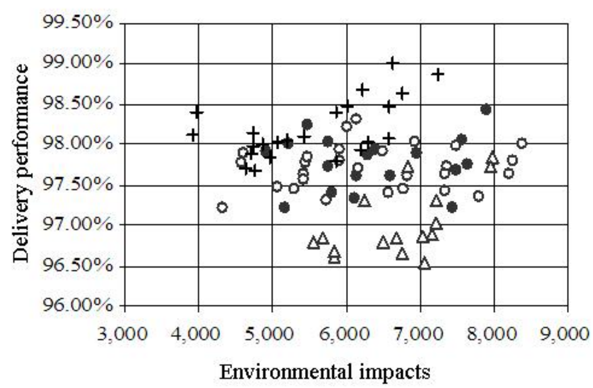

Fig. 6.11 Optimization results (Environmental impacts vs. Delivery performance)

Table 6.6 Statistics of optimization results.

	Disposal	Component reuse	Product reuse	Component and product reuse
Number of Pareto optima	29	16	24	18
Economic costs (avr.)	5754,2	6666,1	5137,7	6203,7
(std.)	1092,4	1249,0	797,3	854,6
Environmental costs (avr.)	6301,6	6719,1	5528,3	6364,9
(std.)	1141,7	743,8	935,6	943,3
Delivery performance (avr.)	97,67%	97,03%	98,19%	97,77%
(std.)	0,22%	0,42%	0,39%	0,34%

Table 6.7 Correlations between weighting criteria and performances

Scenario	Economy	Environment	Delivery
Disposal	0.82	0.78	-0.17
Component reuse	0.76	0.77	-0.37
Product reuse	0.75	0.70	-0.17
Component and product reuse	0.74	0.78	-0.09

Table 6.8 Numeric optimization results.

Indices	w_1	w_2	w_3	max(rp_2)	max(rp_3)	Eco*	Env*	DP*
G1-1	0,87	0,07	0,07			4.274	8.204	97,64%
G1-2	0,87	0,07	0,07			4.294	8.251	97,81%
G1-3	0,87	0,07	0,07			4.383	8.385	98,00%
G2-1	0,07	0,07	0,87			5.903	5.903	97,80%
G2-2	0,07	0,2	0,73			5.978	5.414	97,55%
G2-3	0,07	0,2	0,73			5.988	5.442	97,77%
G3-1	0,4	0,13	0,47	35	44	4.497	5.862	98,40%
G3-2	0,33	0	0,67	36	44	4.923	5.859	97,81%
G4-1	0,07	0,27	0,67	35	43	5.377	4.735	97,97%
G4-2	0,07	0,2	0,73	31	41	5.562	5.202	98,05%
G5-1	0,07	0,73	0,2	32	41	6.685	3.964	98,41%
G5-2	0,07	0,8	0,13	32	43	6.973	3.910	98,13%

Eco: Costs, Env: Environmental impacts, DP: Delivery performance

6.3.4 Reconfigurability analysis

The reconfigurability discussed in this study is the capability of OEMs to achieve performance targets by reconfiguring their supply chain and end-of-life operations. The targets are described in terms of the costs, environmental impacts, and delivery performance. The reconfiguration is specifically performed by changing the parameter values of these operations and by selecting the end-of-life operations (i.e. selection of an end-of-life scenario).

Reconfigurability analysis in single end-of-life scenario

The reconfigurability in the disposal scenario is solely dependent on the supply chain operations, since the scenario does not contain product and component circulations caused by their physical and functional deteriorations. This is why the standard deviation of the delivery performance in the scenario is smaller than the other scenarios. However, this does not mean that the delivery performance of the scenario is better than that of the other scenarios, since in the other scenarios reusable products and/or components are reserved for the increase of the delivery performance.

The reconfigurability in the other scenarios additionally depends on the end-of-life operations that control the number of stored products and components at the OEM. The control of the storage requires a prediction technique as proposed in this study, since the decisions regarding the end-of-life operations should be made in advance of the actual requests of reusable products. Investigation of the methods to control the storage using end-of-life operations will be of the focus of future research using the proposed method.

An increase of reuse and remanufacturing operations naturally decreases the component delivery from suppliers. The net impact of this phenomenon on the performances depends on the relative differences in the specific process performances (e.g., component delivery and product delivery). This is why addition of adjustable parameters (by OEMs) does not simply improve the performances.

In all of the end-of-life scenarios, it is shown in Table 6.7 that the costs and environmental impacts show positive correlations with the respective weight for component order placement to suppliers. Such information is useful in evaluating the ordering criteria of suppliers subject to the supply chain performance. For instance, further investigation about ordering criteria of component suppliers and performance indicators regarding the delivery performance is necessary in order to apply the proposed method for the reconfigurability analysis regarding this performance perspective.

Reconfigurability analysis with end-of-life scenario changes

The reconfigurability analyzed above has been dependent on the parameters of supply chain and end-of-life operations. Here, changes of end-of-life scenarios (i.e., a set of end-of-operations and these execution conditions) are considered for the analysis of the reconfigurability of these operations against stepwise performance target changes. For the sake of simplicity, the reconfigurability is analyzed from the economic and environmental perspectives.

Scenario: At the beginning, the OEM follows the disposal scenario and places component orders to the suppliers according to the order so as to minimize the supply chain costs (G1 in Fig.6.9). Then the OEM targets at a decrease of environmental impact by 25%. The OEM can achieve the target by reducing the component order to the most economically efficient supplier (G2 in Fig.6.9). Alternatively, the OEM can employ the product reuse scenario, while maintaining the order of suppliers unchanged. As a result, the target can be achieved with a less cost increase (G3 in Fig.6.9). Furthermore, the OEM adopting the latter decision can reduce environmental impacts by nearly 50% from the initial state with the same cost increase from G1 to G2 (G4 in Fig.6.9). To decrease environmental impacts by 50% from the initial state, the OEM needs to reuse products and further decrease the component orders from the most economically efficient supplier (G5 in Fig.6.9). Introduction of component reuse is not appropriate in this scenario because the optimization results show inferiority of the component reuse (see Section 6.3.2).

The above scenario indicates that OEMs can decrease the environmental impact by selecting appropriate end-of-life scenarios. The proposed method helps analyze alternative decisions of OEMs regarding uncertain quantitative performance target changes.

6.4 Discussions

Limitations of the proposed method

The major limitation of the proposed method is the availability of information. The method requires two types of information; the information to describe processes and products, and the information to quantify the performances (costs) of the processes. On one hand, as is explained in Section 6.2.1, the description about processes and products are crucial for constructing a life cycle simulation model, and lack of this information influences on the validity of a simulation model. On the other hand, the performance description is necessary to improve the precisions of performance evaluation using a valid simulation model. Although the propose method can be conducted under limited availability of the performance description, the results also limit quantitative precision of the performance evaluation.

Verification of the proposed method

The proposed method is based on the two established technologies; Life cycle simulation (LCS) and multi-objective optimization (MOO). On one hand, the concept and mechanism of LCS has been tested at a number of case studies with collaborations between academia and industry (for instance, Fujimoto et al. 2004). On the other hand, a number of algorithms for MOO have been developed (Coello Coello et al. 2002), and the algorithm implemented for this study is one of them (Fonseca and Fleming, 1993).

However, the proposed method should be further verified through the comparisons between the actual operations of OEMs supported by SCM-ERP systems and the process descriptions of the life cycle simulation model. The comparisons bring the model closer to the actual operations and identify the overlooked variables for operational decisions (e.g., evaluation criteria for the prioritization of suppliers).

Applicability of the proposed method

In applying the propose method to actual design cases in industry, time and costs for executing the method should be compared with the impact of the method on the improvement of design of life cycles. Among the processes for conducting the proposed method, data collection, model construction and interpretation processes require most of the time and costs, while simulation and optimization processes are automated. As described above, the data collection process is inevitably restricted by the availability of information. However, integration of the proposed method with existing SCM-ERP systems decreases the effort for information retrieval. The model construction process can be improved by developing a modeler dedicated to the proposed method. The interpretation process requires experts of both technical knowledge (modeling, simulation and optimization) and the knowledge about design objects (products and life cycles).

Furthermore, the proposed method becomes effective as the number of suppliers, market segments and applicable end-of-life options increase. It is because of that, although the increase of these numbers expends the spaces for searching the optimal configurations, the simulation (i.e., LCS) and optimization procedures (multi-objective genetic algorithm) applied to this method do not change.

6.5 Conclusions

The study presented in this chapter has proposed a method for OEMs to model, simulate, and optimize their supply chain operations considering their end-of-life operations. The method has been useful to evaluate the capability of OEMs to achieve quantitative performance targets, which are defined by environmental legislations or long-term strategic policies. The method has indicated that OEMs can achieve the performance targets by changing the priority of suppliers and by changing the end-of-life operations.

The role of *ISCL* has been crucial not only for the quantitative evaluation of the capability to achieve performance targets, but also for the identification of multiple possible reconfiguration paths to achieve the targets. Furthermore, physical deterioration and functional obsolescence of products are explicitly defined in LCS as stochastic elements considered at the evaluation of this capability. Formulation of supply chain operations and integration of the supply chain operations with a life cycle model used for LCS have been necessary steps to apply LCS to the analysis of the supply chains of OEMs from a life cycle perspective.

Long-term relationships between OEMs and stakeholders in their supply chain and end-of-life process can be designed, while considering uncertainty in future environmental legislation changes. In such a design task, the proposed method is useful for OEMs to analyze an aspect of the robustness of their supply chain from a life cycle perspective.

Remarks related to the research question 1b

In this study, two types of design information, selection of suppliers and selection of end-of-life operations, have been used to describe possible configurations of an OEM supply chain. It was found that information about the performances of individual suppliers was useful to determine the orders of preference among possible selections with respect to a single performance objective. However such individual information was not sufficient to predict the system level performance, the performance deviation, and the order from multiple perspectives. Similarly, design information about possible end-of-life options for a specific product, and about modularity is not sufficient to choose optimal end-of-life options for products and modules from a life cycle perspective. Therefore, it is necessary to either find another information provide appropriate indication about design choices among possible alternatives, or generate such information based on available design information.

Study in this chapter cannot conclude that selection of suppliers and selection of end-of-life options are major determinant of the performances. Other design information can be considered as a source of reconfiguration of a design concept with respect to the performances. For instance, selection of material (Castro 2005) can be appropriate in context of the design of OEM supply chains, and the selection is also related with selection of end-of-life options.

Remarks related to the research question 2a

Life cycle simulation as a function of *ISCL* has been useful in quantifying the multi-objective performances considering a variety of stochastic behavior in a life cycle. Furthermore, such simulation technique is crucial in operational decision making in determining the type and timing of optimal end-of-life options during the life cycle.

7 Considering services in the service industry

In Chapter 6 and Chapter 7, *ISCL* has been applied to the design of services and other operations in product life cycles. In this chapter, the focus of applications extends to business model design for the service industry based on the PSS concept. The case study in this chapter is useful to investigate the differences at the design process in utilizing design information among the case studies in Chapter 5, Chapter 6, and Chapter 7. It is also useful to identify other characteristics of PSS design information and corresponding computational design supports, which have not been addressed in Chapter 5 and Chapter 6. A design process of tourism business for a sustainable destination is chosen as a case to be analyzed using *ISCL*, while considering commonality of the objectives with other PSS based business concepts. The proposed analysis using *ISCL* can be used with existing environmental assessment methods for sustainable tourism business. Information collection, system boundary definition, PSS modeling, initial analysis, new business concept generation, and quantitative sales deviation analysis of business scenarios are presented. This chapter is considered useful for students and teachers involved in PSS design education as guidance to design and analyze a business model following the PSS concept under computer-aided PSS design environment.

7.1 Introduction

Sustainable destinations aim at the continuous growth of regional economy through tourism business using their rich and unique biosphere, while preventing it from degradation. In this chapter, a design process of a business model for a sustainable destination is analyzed using *ISCL*.

The design process is different from those in Chapter 6 and Chapter 7. The case studies in those chapters are considered applicable to the design of business models based on the industrial product-service systems (IPS2) concept. The concept is aimed at value addition in the life cycle of a product by providing diverse service offerings to customers, in which the product is treated as the core service channel (Transregio29 2008). These PSSs are referred to as product-oriented or use-oriented types according to Tukker and Tischner (2006).

PSS design can be solely initiated by the goals of customers without assuming ownership and usages of products by customers. PSSs based on this concept are classified into result-oriented type (Tukker and Tischer 2006). The core of such PSSs is the service receiver that specifies the results to be delivered, while flexibility in selecting products and services remains. This kind of PSSs therefore requires information about products and services in relatively wide domains.

The conceptual difference in generating PSS design concepts from different core elements is shown in Fig. 7.1. In the left concept, services are associated with the life cycle of core products (e.g., machine tools or medical instruments). In the right concept, requirements are defined by the service receivers (e.g., tourists), and necessary services and products are further defined based on them. Tasks of PSS designers are both to identify their tangible and/or intangible service contents under various service offering contexts in a life cycle of the given products, and to find products and services to meet the requirements of service receivers.

Based on the above argument, this chapter is crucial in this study in order to observe a PSS design process from the perspective of service receivers. Through the observation, a cased study in this chapter is aimed at the identification of other characteristics of design information and corresponding computational supports, which have not been addressed in the previous chapters.

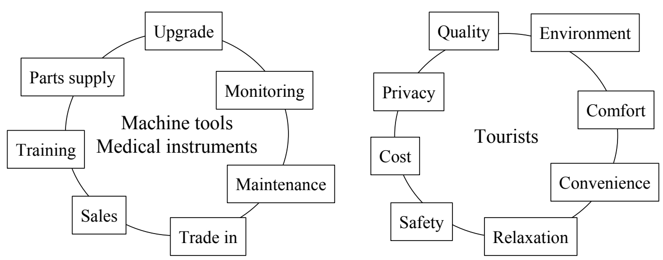

Fig. 7.1 Generating PSS design concepts based on different core elements

Tourism business model design for a sustainable destination is to plan long-term facility investment and utilization specific to the destination from economic and environmental perspectives. The analysis of business model design for a sustainable destination is considered feasible as a case in this chapter, because the objective of the business model is consistent with business models based on the PSS concept. Furthermore, business models based on the PSS concept have been investigated in the mobility sectors and the energy sectors. This also indicates feasibility in extending the PSS concept in context of the tourism industry, in which tourists need mobility from/to/at destinations and they consume much energy than the average.

Before introducing analysis of a business model based on the PSS concept using *ISCL*, it is noted that a number of methods have been investigated to assess environmental performance of tourism business models from a managerial perspective as follows.

Strategic tourism planning is useful to maintain and improve environmental quality, and an environmental approach is simultaneously considered as good economic planning (Edward 1987). Strategic environmental assessment (SEA) evaluates policies and regional plans from an environmental perspective (Therivel 1993). The form of evaluation varies from impact analysis to alternatives suggestions. Kuo et al.(2005) applied a SEA to the tourism sector in Taiwan. The employed SEA method included an impact evaluation approach and the opinions of experts.

Modeling approaches have been studied for environmental design and analysis of tourism business. Xiang and Formica (2007) proposed a cognitive modeling approach to explicitly trace the perception of decision makers in travel industry. The mapping approach was helpful to clarify the complex relations among the various factors influencing their decision makings concerning environmental measurements. However, the model has not used for the design of environmental measurement considering these factors.

Considering tourism business planning (design) as development of new scenarios, several scenario-based environmental systems analysis tools are available (e.g., Moejer et al. 2008). Among them, life cycle assessment (LCA) can be useful for quantitative impact assessment. However, stand alone usage of LCA is not sufficient for the design of a tourism business model from an environmental perspective for two reasons. First, a function unit and system boundary should be defined in terms of the activities of tourists rather than the life cycle of a product. Second, uncertainty in a tourism business model should be explicitly considered (Ramon et al. 2007). For, LCA cannot support probabilistic design and analysis of the model.

Collaborations among stakeholders in different sectors are effective to improve the environmental performance of tourism business, if the stakeholders accept new collaborations, rather than maintaining an economically or politically preferred traditional collaboration (Fadeeva 2005). However, sustainable collaborations are specific to destinations, and there is no standard procedure to form such collaboration (Kernel 2005).

The approach used in this chapter to analyze the performances of a tourism business does not replace or contradict with the above assessment methods in the tourism sector. Instead, this approach can be integrated with other existing assessment methods. It is because the approach can support quantitative design and analysis of a tourism business model considering stochastic tourist behavior, and because the approach enables the designers to consider relations among multiple stakeholders.

This chapter is structured as follows. In Section 7.2, a case study to analyze the design of a tourism business at a sustainable destination is described. This chapter is concluded in Section 7.3 with presenting the characteristics of design information and corresponding computational support offered by *ISCL*, which complements the findings in the previous chapters.

7.2 Tourism model design at a sustainable destination using ISCL

This section conducts a case study to model, analyze, and simulate a business model in a sustainable destination based on the PSS concept using *ISCL*. *Service CAD* (as a part of *ISCL*) described in Chapter 3 is used to model activities of tourists in the business model. Life cycle simulation (Chapter 4) is conducted to evaluate the sales of diverse service providers at the site varying the number of tourists with different preferences.

7.2.1 Background

Ameland is one of the islands in the Waddensea. The island is known for its unique biosphere in comparison with other islands in the same region. By making use of the nature as tourism resource, the local government characterizes Ameland as one of the distinguished destinations for sustainable tourism. For instance, the island currently promotes several projects towards sustainability. Example includes *Waterstof in aardgas* and *Groen licht* in context of Duurzaam Ameland (Amelander 2008). Similar to the other islands in the Waddensea, this policy increases the dependency of regional economy on tourism industry. As indicated in a statistic source, the size of job market in the island has grown by 30 % during the recent 10 years, and the commercial service sector mainly contributes to the growth (CBS 2007).

7.2.2 Defining system boundary

The system boundary of a business model is determined by specifying the activities of tourists included in the model. Definition of the system boundary from the service receiver's perspective indicates that the business model is designed to satisfy the goal of service receivers. Figure 7.2 illustrates three system boundaries related with the tourism business in Ameland.

The outermost boundary is defined by selection of activities of service receiver regarding the way they receive *relaxation*. When this boundary is selected, the performance of tourism business in general is compared with alternative activities that deliver *relaxation* (e.g., take a rest at home). The middle boundary is defined by the selection of destination to receive *experience in nature*. Accordingly, Ameland is compared with other sustainable destination (or virtual experience to deliver *experience in nature*). The innermost boundary indicates how to deliver necessary service contents such as accommodation, mobility, food.

Although the boundary can be refined according to the tasks of the designer, this case study focuses on the innermost layer in Fig. 7.2. It is because this boundary has an appropriate resolution to describe service channels and service providers as elements of alternative business models, and further refinement of the boundary introduces design of individual products and services, which is out of focus of the study based on the PSS concept.

The service contents appeared in the definition of system boundaries are related in terms of a variety of relations. For instance, *experience in nature* is a concretization of *relaxation*, while *accommodation*, *mobility*, and *food* are necessary for *experience in nature* at a sustainable destination. These relations are also appeared at a clean cloth delivery business in Tomiyama et al. (2004).

7.2.3 Information collection

Qualitative and quantitative information was collected in order to analyze the tourism business in Ameland. The types of collected information are as follows.

- Information about tourists and inhabitants in Ameland. Their profiles can be specified with respect to number, age, income level. Furthermore, seasonality of the number of tourists is considered.
- Inventory for the economic activities in Ameland: Products and facilities necessary to deliver specific service contents to tourists and inhabitants. They are specified in terms of the number (or capacity), the delivered service contents and the owners (service providers). The information about the costs and duration of service with these products and facilities are collected.

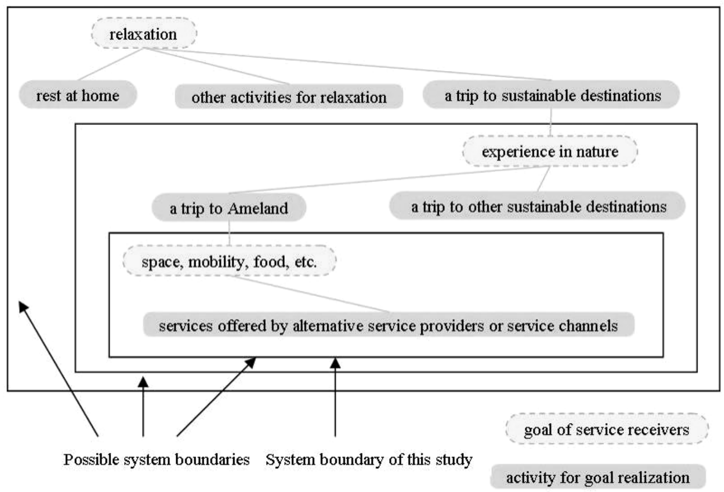

Fig. 7.2 System boundaries for business model development

Currently, the study uses the following sources for collecting information.

- Statistics provided by the government (e.g., CBS 2007)
- Literatures (e.g., Bakker 2005, Krozer 2007)
- Documentation prepared by the tourism office (VVV 2006, 2007)
- Web sites of the stakeholders (e.g., local service providers, municipality and tourism office)
- Site investigation by the authors
- Personal communications with the stakeholders (e.g., local service providers and tourists)

The collected information was summarized in the following tables and figures. Table 7.1 and Table 7.2 summarize statistic information between 1995 and 2007 collected CBS (2007). Table 7.1 shows the characteristics of inhabitants in Ameland. Table 7.2 shows other information that characterizes the island. Table 7.3 shows a cumulative expenditure of two tourists during a trip. It was collected by a field study. This information is used for the initial analysis described in Section 7.2.4. Figure 7.3 shows the increase of the number of tourists and its simplified seasonal deviation in 2005. Figure 7.4 lists service contents, channels and providers appeared at the websites owned by the tourism office. In the study, the specific service costs using these service channels are measured or estimated to analyze the business model at the following subsections. Table 7.4 summarizes the service contents, service channels, and service providers considered in the development of a business model. This information was used in modeling and simulation of the case study in this chapter.

Table 7.1 Statistic information (inhabitants)

	Period 1*	Period 2*
Total		
Male	3,374(1995)	3,460(2007)
Female	1,702(1995)	1,745(2007)
Age distribution	1,672(1995)	1,715(2007)
Under 25	1,131(1995)	1,015(2007)
Between 25 and 45	989(1995)	954(2007)
Between 45 and 65	761(1995)	1,041(2007)
Above 65	493(1995)	518(2007)
Family structure		
Single	453(1999)	490(2003)
Family w/o child	359(1999)	429(2003)
Family with child(ren)	576(1999)	562(2003)
Disposable income [thd. Euro/ Family]		
Single	13.6(1999)	18.0(2003)
Family w/o child	28.5(1999)	33.1(2003)
Family with child(ren)	25.6(1999)	35.1(2003)

Table 7.2 Statistic information (resources)

		Period 1	Period 2
Service channels	Mobility [unit]		
	Passenger cars	1,080(1998)	1,479(2007)
	Motorbikes	152(1998)	226(2007)
	Trucks and trukters	289(1998)	459(2007)
	Space [unit]		
	Individual houses	1,561(1995)	1,820(2007)
	Recreation houses	1,166(1995)	1,286(2007)
	Landuse		
	Land [km^2]	57.30(1995)	59.18(2007)
	Water [km^2]	211.20(1995)	209.32(2007)
	Building [%]	2.1(1996)	2.3(2003)
	Nature [%]	56.5(1996)	55.6(2003)
	Recreation [%]	4.0(1996)	4.3(2003)
	Agriculture [%]	36.6(1996)	34.1(2003)
	Public road [km]	114(2001)	119(2006)
Employment	Total [thousand]	1.09(1999)	1.20(2003)
	Service (commercial)	0.62(1999)	0.76(2003)
	Service (non commercial)	0.28(1999)	0.28(2003)
Others	Domestic animals [unit]		
	Cows	3,313(1995)	2,651(2006)
	Chickens	3,600(1995)	2,190(2006)
	Others	10,964(1995)	6,793(2006)

Table 7.3 Reference expenditure of a tour

Descriptions of tourist activities	Service contents	Expenditure [Euro]
In mainland: Drive between home and Holwerd (the harbor at mainland) (return)	Mobility	50 (Fuel) 23 (Parking)
In Ferry: Ferry between Ameland and Holwerd (return)	Mobility	22 (2 adult tickets)
In Ameland: (two nights)		
Transportation (public transportation, rental bike)	Mobility	15
Stay at a hotel	Accommodation	120 (2 nights)
Other activities	Others	40
Total:		243

Table 7.4 Service contents, channels, and providers

Service contents	Service channels and service providers
Energy	Centralized or decentralized power sources and infrastructure of different energy types (solar energy, natural gas, bio fuel, etc.)
Water	Government
Accommodation	Hotel, Holiday house, Camping site
Mobility (mainland)	Train, Airplane, Passenger car
Mobility (mainland - Ameland)	Ferry
Heavy Mobility (Ameland)	Bus, Taxi, Passenger car
Light Mobility (Ameland)	Bicycle
Food and drink	Bar, Restaurant, Supermarket
Experience	Guide tour (nature, culture), concert, exhibition, museum
Nature	Landscape, Bird, Domestic animal
Health	Doctors, Medical device, Hospital,
Information	VVV (tourist office)

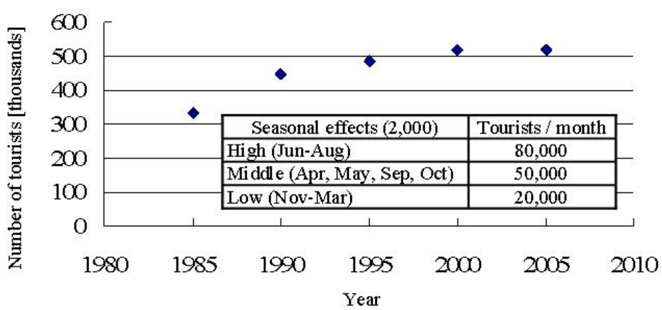

Fig. 7.3 Tourist progress and seasonal deviation

Swimming pool (2)	Discotheque (2)	Restaurants (33)	Sightseeing spots (5)
Tennis court (5)	Rental bicycle (12)	Pottery course (1)	Night excursion (1)
Sauna (7)	Rental bike shops (1)	Museum (4)	Sports fishing (1)
Tanning beds (7)	Massage (1)	Village for visit (4)	Trucker tour (1)
Parachuting (1)	Beauty salon (2)	Museum tour (2)	Coach (4)
Horse riding (4)	Game center (1)	Nature tour (2)	
Golf field (1)	Sea bathing (4)	Ferry tour (1)	
Bowling (2)	Bars (20)	Mud walking (2)	
Gym (2)	Cafeteria (18)	Nordic walking (1)	

Fig. 7.4 Distributed facilities

7.2.4 Modeling a tourism business model

A business model includes a set of activities within the predefined system boundary (Fig 7.5). In this case study, it includes a return trip between the home of tourists and Ameland, and various activities in the island. Each activity delivers one of the following five service contents; *heavy mobility*, *light mobility*, *accommodation*, *food*, and *others*. Alternative service channels and service providers exist for the delivery of service contents, they are obtained from the collected information. These alternative activities in a business model indicate that the behavior of tourists is stochastic. Influence of probability to determine the stochastic behavior of tourists on the performance of the business model is also considered using PSS life cycle simulation (see Section 7.2.7).

7.3.5 Initial investigation

Initial investigation is conducted in terms of macroscopic business figures in Ameland. It also analyzes constraints of the service delivery. Such investigation can be useful to identify necessary products and facilities to increase the capacity in service delivery. Quantitative assessment of the constraints is crucial for systematically planning new investments of service channels and their usages.

- *Regional economy:* The amount of total disposable income in Ameland due to commercial activities has increased from 19.3 million Euro (1999) to 32.5 million Euro (2003). This is interpreted as an increase of value added of tourism business per tourist from 38.6 Euro (1999) to 65.0 Euro (2003). These values are 16% (1999) and 27% (2003) of the expenditure per tourist, respectively. On the contrary, other economic activities such as agriculture and farming have been diminishing.
- *Accommodation:* A study shows that the total number of bed-nights in 2000 is 2.1 million Euro (Bakker 2002). This indicates that the average number of stays of tourists is four days, which requires around 10,000 beds in high seasons. However, the same report shows the number of beds in the same year is 27,000. This can be interpreted that the increase of holiday houses in Ameland is driven by the changes of preferences of tourists rather than the lack of capacity to provide accommodation for them. As a result, increases of housing vacancies are expected.
- *Mobility:* The amount of heavy mobility in Amalend largely depends on the number of passenger cars owned by inhabitants and brought by tourists. First, almost all families in the island own a passenger car in 2007, while the rate was 80% of all families in 1998. This indicates that the increase rate has already arrived at the peak, although it has been significant during the years. Second, the number of passenger cars brought by tourists is constrained by the capacity the ferries in service between the island and the mainland (1,000 passengers and 48 cars) and the frequency of service (68 returns/week at high seasons and 39 at low seasons). (VVV 2007; Bakker 2002). In an extreme case, daily 500 cars are brought from the mainland and the total number of cars in the island proportionally increases with respect to the length of their stay.

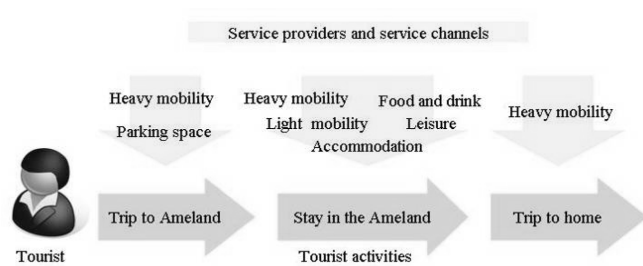

Fig. 7.5 Tourist activities in a business model

7.2.6 Generating sustainable business concepts

This subsection introduces a business concept of mobility service for the tourists in Ameland, using renewable sources combined with a waste management service. The business model is developed by a group of graduate students at the faculty of industrial design engineering of Delft University of Technology. The detail is described in a report (Versteeg et al. 2008). The concept is included into the developed business model in Section 7.2.4. The feasibility of the concept from economic perspective is evaluated in the context of the business model.

The concept is shown in Fig.7.6. The concept consists of three stakeholders (*tourist*, *bio bus company* and *bio fuel factory*), and includes five activities (*stay*, *collect waste*, *trade waste and bio fuel*, *product bio fuel* and *transport tourists*). The main activity *transport tourists* delivers *heavy mobility* to *tourists*, while other activities generate the flows of *money*, *waste* and *bio fuel*. The *bio-bus company* owns a *bio-bus* as a service channel to transport the waste and tourists. Furthermore, the mobility service is provided free of charge, as long as they collect and separate their own waste during *stay* in the island.

In order to evaluate and improve the feasibility of the proposed bio-bus based business concept, the following measurements and suggestions have been made by the designers.

- Integration of *collect waste* and *transport tourists* decreases the bio fuel consumption. However, quality of the tourist transportation can decrease due to strong smell of the bio waste. The bio-bus or containers for bio waste should be therefore designed to prevent the smell from reaching the tourists. This suggestion added *quality* of the transportation service as one of the specification, and it is related with *odor* perceived by the tourists during the service.
- Capacity of waste is instable due to deviation of the number of tourists. Moreover, it is small compared with production capacity of a reference biomass plant in a preceding case study (20t/day) (Biomass Information Head Quarter, JORA 2008). Therefore, integration of the business with other resources (such as domestic animals) is useful to maintain the amount and stability of the waste delivery. This suggestion is based on the fact that the statistic information in Table A.3 includes the number of domestic animals.

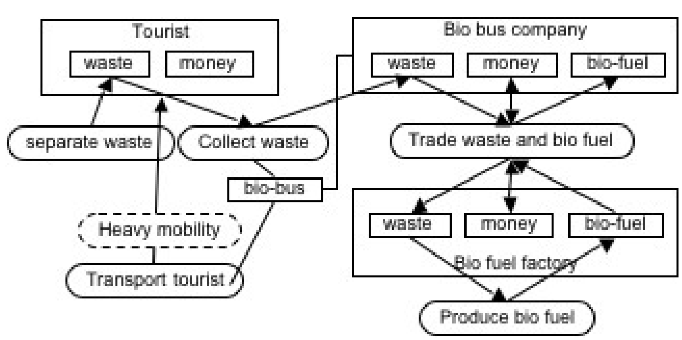

Fig. 7.6 A business model using a new service channel by the designer

In addition, Fig. 7.7 illustrates the evaluation of economic feasibility of the concept. The service delivered by this concept is compared with other alternative heavy mobility services available in the island (taxi, public transportation, and passenger car brought by tourists). The service fee is constrained by the tourists and other stakeholders as follows.

- The fee of the transportation service with the bio-bus should be smaller than the fee with public buses. Increase of the service fee therefore needs other value addition (e.g. on-demand transportation service to increase convenience of the service).
- The service fee should be balanced with the cost of activities by the bio-bus company and the bio fuel producer in Fig. 7.6. Furthermore, the cost of these activities depends on the bio fuel production plant and the separation and collection processes. Outsourcing waste separation to tourists may decrease the cost.

New business concepts were derived from this concept. For instance, the bio-bus was considered as a service channel to deliver other service contents to the tourists.

- Delivery of information: Useful information for the tourists is presented in the bio-bus. In addition, the bio-bus takes the tourists to the specific places appeared in the presented information. Potential stakeholders of this service include VVV (tourist office) and other restaurants and amusement parks, which needs frequent update of information (e.g. special dish of the day).
- Delivery of food and drink: Tourists take light meals in the bio-bus. The wastes are directly collected in the bus. Potential stakeholders include local restaurants in the island. For instance, the restaurants can prepare a lunch box based on unused cooking ingredient.

This derivation process is useful to identify potential stakeholders. The following examples can be also applied to other transportation means (i.e. normal buses and ferries).

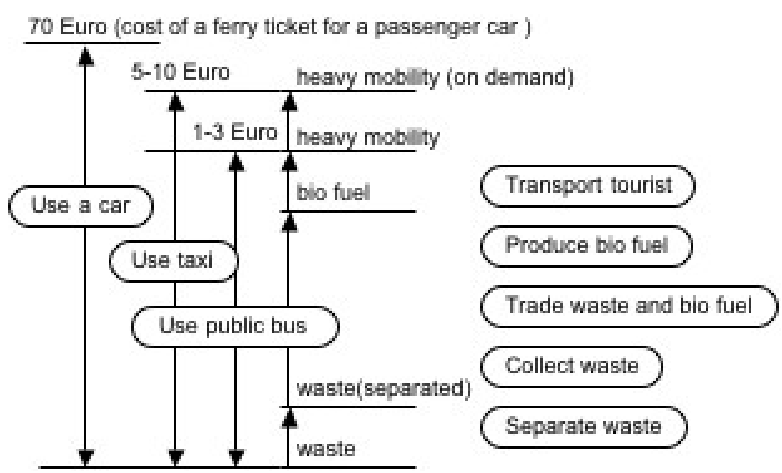

Fig. 7.7 Comparison of the service fee of heavy mobility services

7.3.7 Tourism business sales analysis using LCS

This study analyzed the sales of service providers in Ameland by simulating the behavior of tourists using LCS. The total sales in the island are determined by accumulation of the sales by division in Fig. 7.8. The simulation model was based on the developed business model in Section 7.4.3. The simulation was conducted with different tourist types (*family*, *elderly*, and *business* tourists). They have different probability sets to select service channels and service providers, hence different behavior. Figs 7.9 – 7.14 show the progress of modeling process using *ISCL*. Scale of the simulation in terms of the time resolution and the tourist number, simulation procedure, and simulation parameters, are summarized as follows.

- *Scale:* The scale of simulation model is determined by the number of tourists and the unit time. The scale influences the precision and duration of simulation. Since the precision and the duration is conflictive, a trade-off between them should be found. This study therefore developed a simulation model with a 1/100 scale in terms of the number of tourism at a high season (80,000 tourists per month, or 2,500 tourists per day), and one hour was chosen as the unit time of simulation. The unit time was determined by the frequency of public transportation in Ameland and boats between Ameland and the mainland.
- *Tourist generation:* A number of tourists (determined by the scale) are instantiated in the simulation model. When instantiated, a tourist type (family, elderly and business types), stay length are determined. In the simulations for model verification, 100 tourists are instantiated at the beginning of simulation, while the simulation for a large-scale sales analysis instantiates tourists according to the schedule of ferry from the mainland to Ameland.
- *Tourist activities:* A set of activities composes the behavior of tourists. Each activity specifies its timing and duration of execution. An activity occurs at a simulation time and continues for the given duration. Next activity occurs after completing the current activity. The duration of sleep activities is seven hours, and that of the rest activities is one hour.

To determine the timing of activities this study introduces a decision tree. At every completion of an activity, each tourist instantiated in the simulation looks at the decision tree to determine the next activity, taking the actual simulation time and the tourist state as parameters. Behavior of the tourists is stochastic, because probabilistic parameters are used at some branches in the decision tree.

- *Parameters:* As described above, the decision tree to determine tourist activities include such parameters as activity duration and probability of activity occurrences. Service fee for each activity is given with respect to tourist types (Table 7.5). Other simulation parameters are described in Table 7.6.

To verify the simulation model, relatively simple simulations were conducted with each tourist type. Table 7.7 shows the simulated average expenses of 100 tourists (three nights four days). The simulations results were confirmed by the designers. As is shown the expenses were different with respect to the tourist types. The differences resulted from accumulation of the decision makings by tourists at selection of service channels and service providers.

Table 7.5 Service fees

		Unit	Sales division:	Family	Elderly	Business
A01	Drive to port	Euro/action	Petrol shop	20	20	20
A02	Parking at port	Euro/action	Parking	10	10	10
A03	Take a train and bus	Euro/action	Train and bus	30	30	30
A04	Take a boat		Sea transport	70/10*	70/10*	70/10*
A05	Stay at a hotel	Euro/night	Hotel	10	10	10
A06	Stay at a holiday house	Euro/night	Holiday house	50	50	50
A07	Stay at a camping site	Euro/night	Camping site	40	40	40
A08	Rent a bike	Euro/trip	Rental bike	30	30	30
A09	Take a taxi	Euro/action	Taxi	7.5	7.5	7.5
A10	Take a public bus	Euro/action	Bus	5	5	5
A11	Have lunch at restaurant	Euro/action	Restaurant and bar	3	3	3
A12	Have dinner at restaurant	Euro/action	Restaurant and bar	10	10	10
A13	Drink at bar	Euro/action	Restaurant and bar	20	20	30
A14	Prepare dish	Euro/action	Supermarket	5	5	5
A15	Visit tourist office	Euro/action	Tourist office	10	10	10
A16	Visit museum	Euro/action	Museum	5	5	5
A17	Visit souvenir shop	Euro/action	Shop	5	5	5
A18	Take a return boat (included in A4)					

Table 7.6 Other simulation parameters

	Family	**Elderly**	**Business**
Length of stay [day]	4	4	2
The proportion of incoming tourists [%] (Friday: total=55)	10	10	80
The proportion of incoming tourists [%] (except Friday: total =20)	50	50	0
Mobility (drive to take, drive to park, train and bus)	25/25/500/0/100/0/0/100		
Bicycle carried (yes/no)	50/50	50/50	0/100

Table 7.7 Simulated average expenses of tourists [Euro]

Expense types:	**Family**	**Elderly**	**Business**
C1:Petrol shops	9,2	0	0
C2:Parking	2	0	0
C3:Train and bus	16,2	30	30
C4:Sea transport	25,6	10	10
Mainland total	53	40	40
C5: Hotel	54,5	107,5	200
C6: Holiday house	82,8	80,8	0
C7: Camping site	27	0	0
Island accommodation total	164,3	188,3	200
C8: Rental bike	8,6	7,9	0
C9: Taxi	1,5	3,3	1,7
C10: Bus	5,5	8	7,9
Island mobility total	15,5	19,2	9,6
C11: Restaurant and bar	85,4	83,7	220,7
C12: Other foods and drinks	39,6	45	0
Foods and Drinks total	125	128,7	220,7
C13: Souvenir shops	22,5	27,3	22,9
C14: Tourist office	3	3,4	5,9
C15: Museums	8,7	9,1	5,4
Island others total	34,2	39,8	33,2
Island total	339	376	463,5
Trip total	392	416	503,5

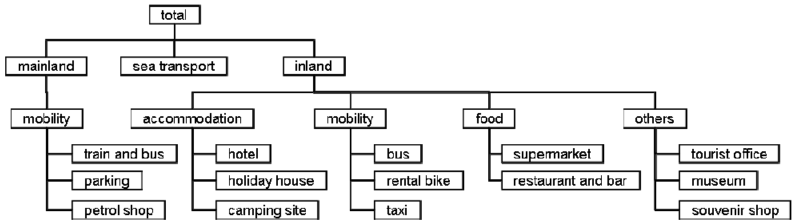

Fig. 7.8 Sales divisions

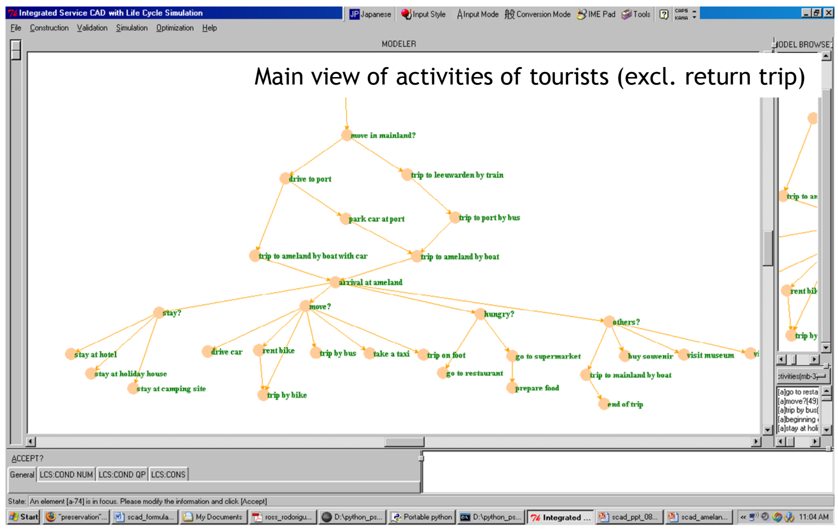

Fig. 7.9 Progress of modeling process using *ISCL* (a)

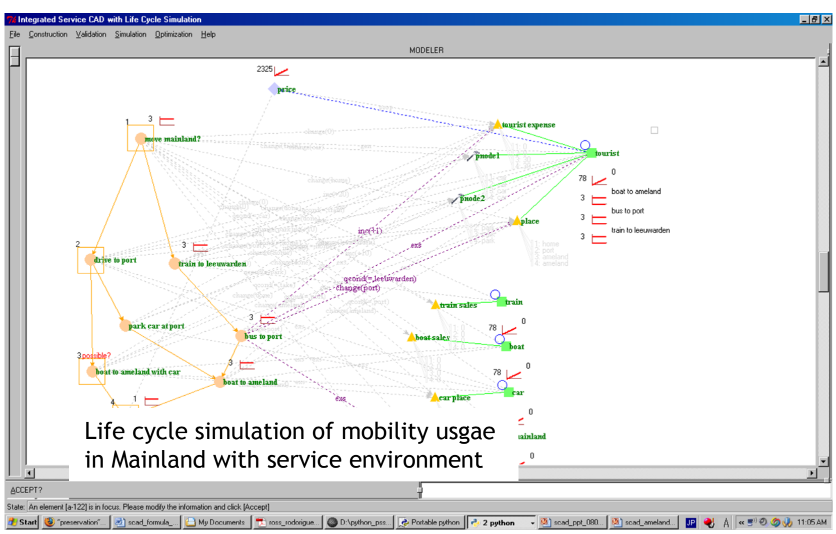

Fig. 7.10 Progress of modeling process using *ISCL* (b)

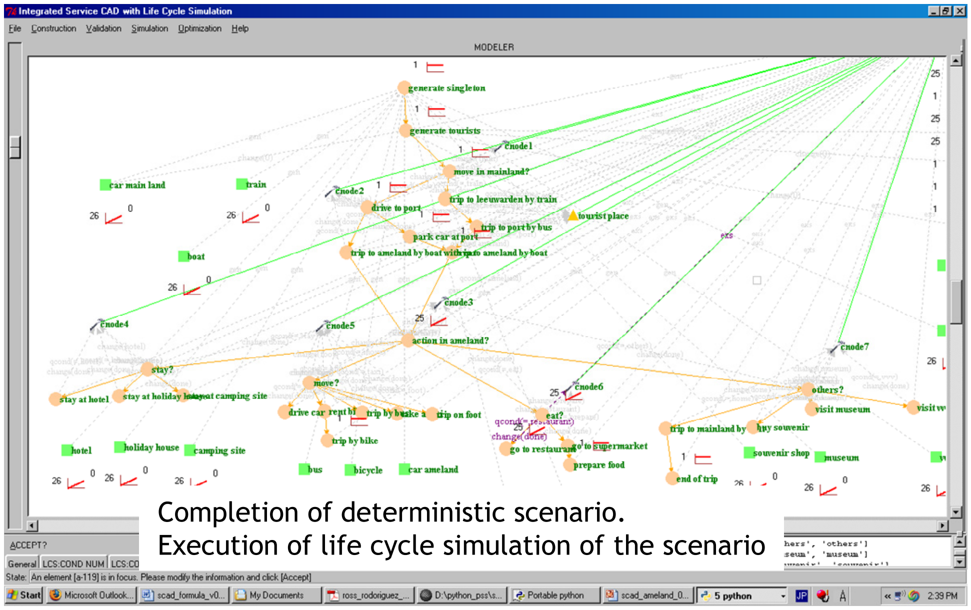

Fig. 7.11 Progress of modeling process using *ISCL* (c)

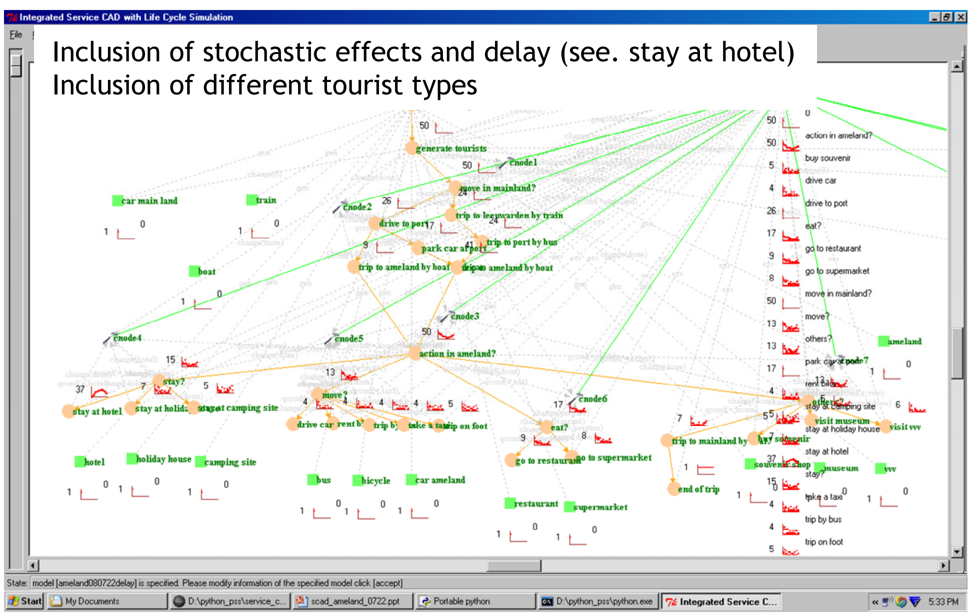

Fig. 7.12 Progress of modeling process using *ISCL* (d)

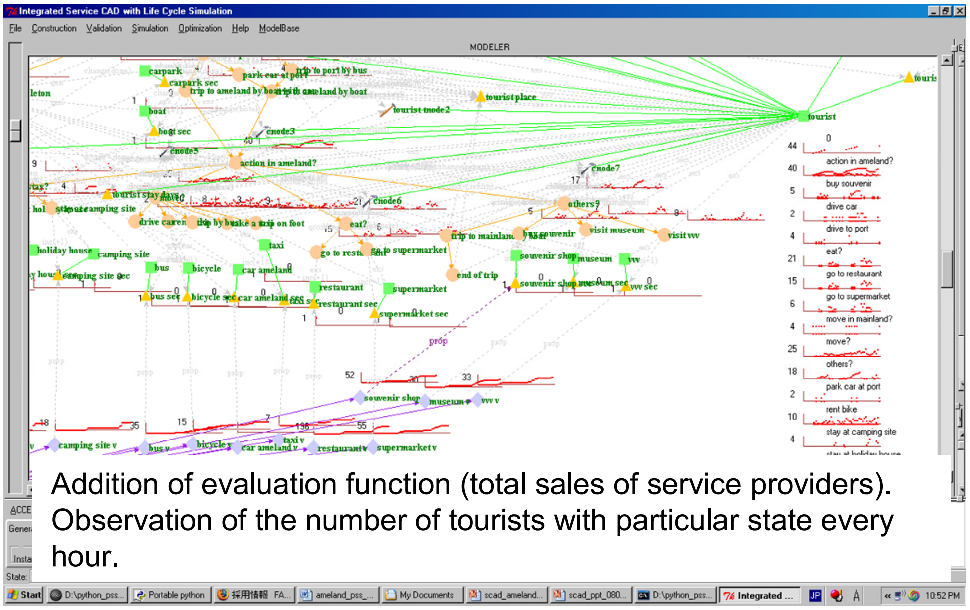

Fig. 7.13 Progress of modeling process using *ISCL* (e)

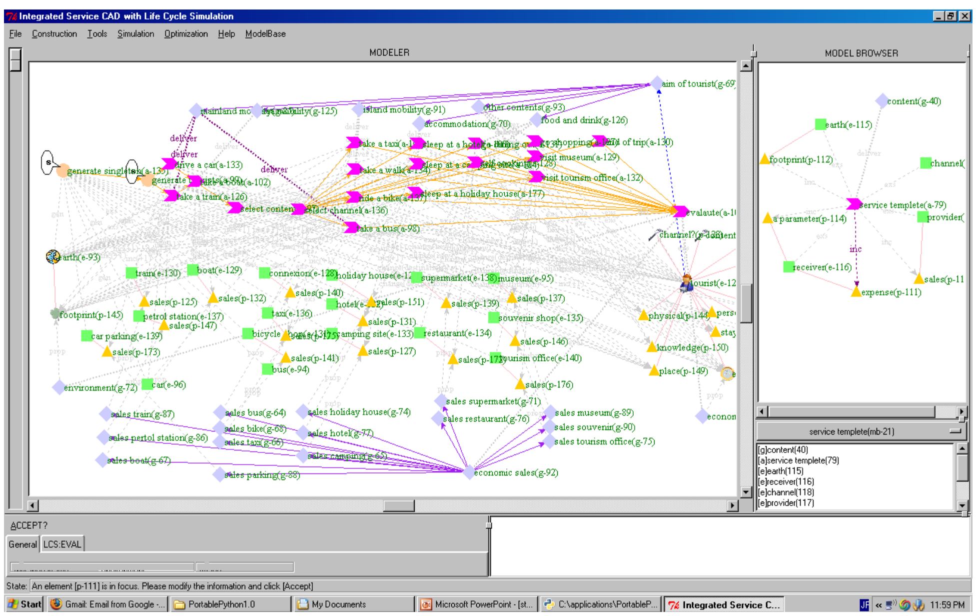

Fig. 7.14 Progress of modeling process using *ISCL* (f)

The simulation model was used for a large-scale tourism service sales analysis. The simulation included a number of tourists, whose type and timing of arrival at the island are varied. The duration of simulation is 30 days (or 720 simulation time units) and the scale of simulation is 1/100 in terms of the tourist numbers at a high season (80,000 tourists per month, or 2,500 tourists per day).

Using this simulation, deviations of the sales of a new business model from the sales of conventional business model is estimated. For instance, a new business model expects additional weekend tourists on Friday. Figures 7.15 and 7.16 show the simulation results of two scenarios and the deviation between them in terms of the sales progress and the tourist number in the island, respectively. The deviation analysis is useful to determine the contribution of certain changes of simulation parameters to the total sales. Evaluation of such a system level performance and its deviation has not been estimated by the designers before conducting this study. The deviations can be broken into a set of deviations at the sub sales by division. Furthermore, the analysis can be useful to identify the constraints of business model in terms of the capacity of service channels compared with growing demands (e.g., by increasing tourists).

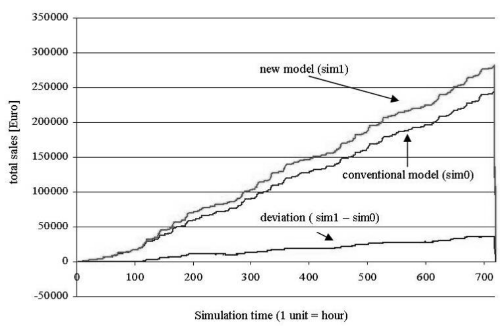

Fig. 7.15 Sales deviations

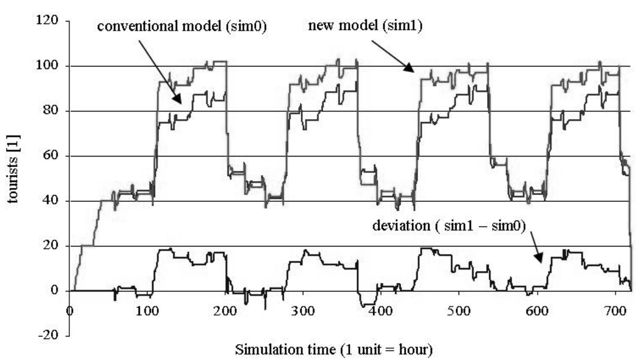

Fig. 7.16 Sales and number of tourists

7.5 Conclusions

This chapter has applied *ISCL* to the analysis of a design process of a business model for a sustainable destination based on the PSS concept. It was found that *ISCL* could support various tasks in analyzing a business model design based on the PSS concept for a sustainable destination. It was also found that the business model design process has required information about products and services in diverse domain, including information about the state of destination. This finding is considered common in business model design in the service industry, which has flexibility in selecting the types of products to satisfy the needs of customers. This chapter is concluded with the following remarks regarding additional aspects to be considered in PSS design for the service industry in dealing with design information and in utilizing computational supports for the design process. The remarks are listed with respect to the related research questions in this study.

Remarks related to the research question 1b

System boundary is one of the design information types to define the scope of design concept generation and design concept evaluation. In comparison with other case studies in the previous chapters, which implicitly assume a life cycle of products as system boundary, explicit definition of the system boundary is necessary for a design concept, which focuses more on the activities of service receivers than the processes in the life cycle of products.
Considering stochastic behavior of such service receivers as tourists, necessary capacity of service channels to deliver the specified service contents should be explicitly analyzed and defined. The analysis is difficult because, the needs are spatially and temporally distributed, and services introduced in the design concept may change the behavior of service receivers, hence the distribution of the needs of service channels.

Remarks related to the research question 2a

ISCL has supported simulation of activity occurrences in service environment (i.e. behavior of tourists at a sustainable destination) distributed in time and space. This function is useful in resolving the difficulty in estimating the necessary capacity of service channels, or the number of service channels with a given capacity.

This function can be extended for the assessment of a long-term investment plan, in which changes of the capacity and number of service channels are taken into account. To do so, the simulation function of *ISCL* should model both microscopic behavior of service receivers and macroscopic changes of the service channels in service environment.

Remarks related to the research question 2b

As described in introduction, the case analyzed in this chapter is based on an PSS design assignment given to a team of students. In developing a new business concept shown in Section 7.3.6, they divided the tasks of individual team members into analysis of available bio-fuel technology, analysis of mobility situation, and modeling of a business concept using *ISCL* (Versteeg 2008). This task division is consistent with the proposed task divisions in the previous chapters.

8 Conclusions and recommendations

In the final chapter of this dissertation, conclusions regarding the research questions of this study are drawn, and recommendations regarding the future development and usage of CAD/CAE tools in PSS design process are described.

8.1 Introduction

The objective of this study was to improve Product Service Systems (PSS) design process by developing a prototype of Computer Aided Design and Computer Aided Engineering (CAD/CAE) tools dedicated for the design process. The design process in this study is considered as designer's systematic information creation activity. The objective was formulated based on the insufficiency of existing methods and tools used by designers in PSS design processes. To overcome the insufficiency, this study considered the applicability of CAD/CAE tools, which have improved productivity in product design processes in the past, to PSS design processes.

Two research questions have been formulated based on the research objective (RQ1 and RQ2). A set of assumptions has been introduced to define the scope of this study. The research questions are about utilization and organization of PSS design information. Each research question has been divided into two sub-questions (RQ1a, RQ1b, RQ2a, and RQ2b). To clarify the possible generalization of the answers to these research questions and the domains of application of these answers, several delimitations of this study have been formulated.

To achieve the research objective, the study has first focused on the representation of design information used in PSS design processes, because formalization of the representation is crucial to effectively use computational supports in a PSS design process. The review of study about life cycle modeling and service modeling has identified the current state of the available representation. The review has identified the necessary extensions of the reviewed method as a representation on CAD/CAE tools for PSS design. As a result, the review has formed the answers to RQ1a.

In this study, *Service CAD* and *ISCL* have been developed for this study to be able to answer the rest of research questions (RQ1b, RQ2a, and RQ2b). These tools are considered as a prototype of CAD/CAE tools for PSS design.

Three case studies to model and analyze the design of PSSs have been prepared to answer the research questions RQ1b, RQ2a, and RQ2b using these tools. These case studies have been useful to identify the design information critical to model and evaluate PSS design concepts using these tools. These case studies have been useful evaluate the functions of these tools in utilizing and organizing design information used in the PSS design processes.

8.2 Conclusions

The following conclusions regarding the research questions are drawn.

Research Question 1: Which kind of design information is/will be used in PSS design processes, and how will they influence the design of PSSs?

> *RQ1a: What is the utility of methods and tools currently offered in academia in dealing with design information in PSS design process, while considering the research findings about the PSS concept?*

- The reviewed life cycle modeling methods and tools can be used for the evaluation of PSSs. LCS in Section 2.1.2 and dynamic methods in Section 2.1.4 deal with stochastic phenomena in a product life cycle. They are useful in designing PSSs, because the performance is derived from the parameter values of products, product users, and manufacturers. The parameters are defined and their parameter values are explored during the design process. Moreover, the capability of LCS to track the behavior of individual products, product users, manufacturers, is useful in evaluating PSSs, in which diverse services are delivered to individual product users and diverse end-of-life operations are applied to individual products.
- The reviewed life cycle modeling methods and tools cannot support building of a life cycle model (rather than evaluation of a given life cycle model). The *building* here means an activity to define parameters of products, product users, and manufacturers, and processes (ore services) to relate these parameters.
- The reviewed service modeling methods and tools compensate the reviewed life cycle modeling methods in the model building process. Considering the model building process as a design activity in PSS design process, service modeling methods should explicitly represent design information classified into design objects (actors, products, and activities (services) by the actors using products), specifications (goals and quality criteria), and the correspondence among them (e.g., how services realize goals).
- The current modeling methods used by PSS designers (Section 1.1.2 and Section 2.2.4) are not sufficient, because these methods do not explicitly classify design information used in PSS design process into design objects, design specifications, and the correspondence among them. For instance, the PSS design guideline (UNEP 2002) defines the sustainable radars as performance indicators (design specifications). However, the guideline does not define a method to evaluate the design of a PSS (a design object) with the radars.
- Among the reviewed service models developed in the field of engineering design (Section 2.2.5) include all three types of design information. However, investigation on these methods is necessary for the development of service CAD/CAE tools for PSS design. Especially, study of formal methods, based on

these service modeling methods, to systematically build PSS models, is necessary. Furthermore, these PSS models can be used for the evaluation using the reviewed life cycle modeling methods through an appropriate integration.

RQ1b: Is there any implicit design information useful in PSS design information, and what are the effects of explicit usage of such information at specific tasks (e.g., modeling and evaluation) in PSS design process?

- Design information about relations among services was often implicit in PSS design processes. This information is crucial for the evaluation of PSS design concepts, in which multiple services exist at the same time or they are integrated into a single service package. Since the information cannot be defined in an independent service description, it is not the scope of the design of a service, but that of a service system (to be included in PSS design processes).
- To evaluate the performance of a set of services in a PSS, temporal and special distribution of quantitative occurrences of the services is crucial. Such distribution is determined by the number required service channels and their capacity. Therefore, this quantitative information should be explicitly included as design information defined in PSS design processes.
- Design information to relate the goals and quality criteria specified by customers and the parameters of products should be explicitly defined. Moreover, design information about services in a product life cycle should define how the services influence the parameters of products.
- For the modeling and evaluation of a PSS design concept, the system boundary should be explicitly defined. System boundaries can be defined differently according to the main stakeholders of PSSs. Similar to the boundary used for life cycle assessment (LCA), the system boundary of a PSS designed in the manufacturing industry is a life cycle of products. The system boundary of a PSS designed in the service industry (e.g., tourism) can be the life cycle of service receivers (e.g., tourists).
- Considering the behavior of product users and the functional and physical deteriorations of products in a PSS design process, the design information should be quantitative and the information should explicitly include probabilistic descriptions. Since the performance evaluation of a PSS including this information is a complex task, simulation-based techniques such as life cycle simulation (LCS) is necessary to complete the task. With such a technique, redesign of a PSS by adjusting the parameter values defined in the PSS becomes possible. Moreover, the economic and environmental feasibility of a PSS depend on the selection of these parameter values.

Research Question 2: How can the information identified by answering RQ1 be organized and utilized for computer-aided systematic PSS design?

RQ2a: How can CAD/CAE tools support/delimit the organization and utilization of design information for systematic PSS design?

- *Service CAD* supports generation of PSS design concepts. Design information used in the PSS design process is organized as a set of PSS models and stored in

Service CAD. The individual models are considered as primitives to construct another PSS model. This supports reuse of design information used in the PSS design process.

- The formalization of design information employed on a CAD/CAE tool is a determinant of its functions. *Service CAD* (developed through this study) supports the development of PSS design concepts based on reasoning. This function requires division of the design information into design objects and design specifications, whose correspondences are formally measurable. This function is not equipped with the currently available service CAD tools (e.g., Service Explorer in Hara et al. (2008)).
- The design information stored in a CAD/CAE tool is a determinant of the performance of its functions. Using *Service CAD*, designers of PSSs manually organize the design information following the formalization (see Chapter 3). First, they classify the design information into the elements of the formalization. Second, they construct primitives by relating these elements. Third, they define the class-level design information to relate these primitives. Further research is necessary to automate or guide such organization of the design information.
- *ISCL* supports the evaluation of qualitative performance of PSSs, in which probabilistic descriptions can be included. The support is realized by integration of a life cycle simulator into *Service CAD*. This support simulates the occurrences of activities (and services) distributed in time and space.
- Visualization of design information used in PSS design processes was one of the delimitations of this thesis. *ISCL* (including *Service CAD*) can be used to study methods for the visualization.

RQ 2b: How can the design information organized for systematic PSS design using CAD/CAE tools influence the tasks of PSS designers and the distribution of tasks among members in a PSS design team?

- *Service CAD* requires the design information used in a PSS design process to be stored following the employed formalization. It also specifies collection and organization of the design information. As a result, tasks of the designers in a PSS design team can be divided into several sub tasks as follows.
- Using *Service CAD*, collection of the information about individual products and services can be separated from the utilization of the information. The former task can be done by experts at specific product and service domains, while the latter task can be performed by PSS designers to generate PSS design concept.
- The above task division assumes that information to relate individual design objects with the corresponding specifications (products and their functions, services and their goals) is given by the domain experts. The task of the domain experts cannot be performed on product CAD tools, because they do not normally store the information about functions (except function CAD tools introduced in Section 1.1.3). For this reason, *Service CAD* is an appropriate workspace for the domain experts, too.
- *Service CAD* is useful in context of product design, because it supports definition of the parameters of products to be measured and changed in a PSS. Furthermore, a function of *Service CAD* that suggests new activities stored in its

database (see Chapter 3) adds new parameters to existing products in a PSS by assigning products defined with the activities to these existing products.

- Introduction of *ISCL* can divide the tasks of designers in a PSS design team. Different types of expertise are necessary to conduct modeling on *Service CAD* and evaluation using a life cycle simulator. This task distribution is different from that proposed above. The division proposed here is based on the expertise about operation of these computational tools.
- *ISCL* has been used for education of students in the course of PSS design (see Appendix A). Limitations of the users in conducting design tasks in computer-aided PSS design environment have been observed. Although, they have sufficiently acknowledged the usefulness of the functions of *Service CAD* in developing PSS design concepts, they had difficulty in including quantitative and probabilistic design information for the evaluation of the developed design concepts using life cycle simulation.

8.3 Recommendations

Recommendations to the developers of CAD/CAE tools for PSS design in the future

The following studies are considered beneficial for the increase of productivity of the PSS design process using CAD/CAE tools in the future:

- Visualization of PSS design information in the design process.
- Construction of a knowledge base used in the design process.
- Automatic acquisition of PSS design information and automatic classification of PSS design information following a formal PSS model.

Although the automatic classification can be beneficial for the increase of the productivity, this study indicates its difficulty as described in Chapter 3.

Recommendations to the researchers of the PSS concept

Most of the studies about PSS concept have focused on the analysis (observation) of the concept (e.g., “What is the PSS concept?” or “Does the PSS concept bring system level sustainable innovation?”). Needless to say, these studies are necessary to understand the PSS concept from a scientific perspective. Nevertheless, this study has shown that case-by-case analysis is necessary to evaluate the performance of business models based on the PSS concept. Therefore, further studies to relate the accumulated scientific findings about the PSS concept with the systematic increase of the performance of PSSs. For instance, sustainability indicators can be studied in terms of relations of the indicators with parameters of products and services. Study about sustainability policy instruments can be studied in terms of relations of the policy instruments with constraints of products and/or services in a PSS.

Recommendations to the users of CAD/CAE tools for PSS design

Introduction of CAD/CAE tools in PSS design processes can change the tasks of PSS designers. Therefore the PSS designers need to understand the difference between the tasks of product designers and those of PSS designers. It is also noted that product design is not a necessary condition for PSS design.

As indicated in the comments by the users of *ISCL* (see Appendix A). Function of *Service CAD* included in *ISCL* helps the users reason relations among the design information (goal, quality, activities, and environment and its parameters) in a PSS design concept. It is recommended for the users to explicitly define such relations on *ISCL* during the entire PSS design process so that other users can understand the implicit design rationale of the users.

Recommendations to the manufacturers and entrepreneurs dealing with PSS design

For the perspective of manufacturers, life cycle design based on the PSS concept can be partly translated to design comprehensive service offerings. As shown in the case studies, the performance of individual service offerings is determined in relation with other service offerings. Therefore, it is suggested to explicitly describe relations among the individual service offerings in order to improve the performance of a life cycle from a systemic perspective.

It is suggested that the design of products and services in context of product- and use-oriented PSSs is appropriate for product manufacturers. The reason here is that customers care value of ownership and functionality of products, which can be improved by service offerings in the life cycle.

Especially, from the perspective of the entrepreneurs, who have flexibility in selecting products and services to satisfy the needs of customers, it is suggested to explicitly specify the required demand of service content delivery distributed in time and space in a service environment. By doing so they can determine the capacity and the number of necessary service channels and additional services to change the behavior of customers, and change the distribution of necessary service content delivery.

Appendix A: PSS design education using *ISCL*

Students have used *ISCL* in a course for the education of the PSS concept. The course is “product service systems” in a master course program offered by Faculty of Industrial Design, Delft University of Technology in 2008 (ID5561). Contents of this appendix were collected (without modification) from the final reports written by the students. In the course, the students have mainly used the functions of *Service CAD*, which were parts of the functions of *ISCL*, due to lack of time to introduce the tool to the students in the course (45 min about the concept of the tool and 45 min for its usage). The final reports can be obtained by course managers (including the author of this thesis). This appendix is use for the readers of this thesis to understand how tool users (students) can recognize the functions of *ISCL* after a short introduction of the tool.

Project A. Sustainable Mobility on the Delft UT Campus

To get a better insight of the important aspects of the proposed PSS, a computer model was created as shown below. In this model the aim was to give an overview of the goals, activities and environment elements that are present. At the same time identify the relations between these elements. After the image, the main findings are presented in key points which highlight some important remarks. The concept was also inputted into *Service CAD* to enable sharing with designers and developers alike, across the world. Users of the program will be able to view our rationale for this design.

Table A.1. Description of the PSS design concept in Project A

Goals	Although most goals are customer oriented, earning money or making the service self-sustainable is also a goal
	Practicing sports is a gathering of several goals as recreation, interaction between students, staying fit, loosing weight, etc. Ensuring quality should be part of the goals as it directly influences the overall performance of the service, from an economic point of view as well as the client satisfaction. Because most goals in the end contribute to the interaction between students they are all linked to this goal.
Activities	The consumption of drinks and food is evaluated by the customer by price, taste and temperature. Although the customers buy drinks to lessen their thirst, it also contributes to the goal of fun as well as interaction between students. The same applies to buying food. Maintenance of the cart and its service is essential to keep the business running. Although the activities are modeled as separate sequential steps, in practice they can take place in a different order and some steps can be skipped as well as combined The precise type and amount of equipment to rent or lend could be determined by experimenting with different goods and the demand from students. The same applies for the food and drinks sale. Offering the different activities (food & drinks and sports equipment) in one cart is better than in separate carts as it is self-promoting. Nevertheless, if the demand increases separate carts are needed as they have a limited the carrying capacity.
Environment	As the cart driver has direct interaction with the customers, he/she will influence the performance of the service. The cart driver can be seen as the link between the different stakeholders and the customer. The suppliers of the sport centre are important, as they determine the quality of the food and drinks. The quality (taste, temperature and price) of the food and drinks is also determined by the cart and how it is modified to these purposes.

Project B Flex Energy; save money, save the environment

Service CAD shows that the core activities in this Product Service System are providing appropriate information about energy to the user and encourage them to consume less. Through those activities consumer can get useful knowledge and wise energy usage. If the activity is repeated the consumer will become more skilful and will be able to take better advantage of the service. The main goal of these activities is that consumers achieve energy-savings (also in terms of money) and that they contribute to a reduction of the total energy consumption of Rotterdam.

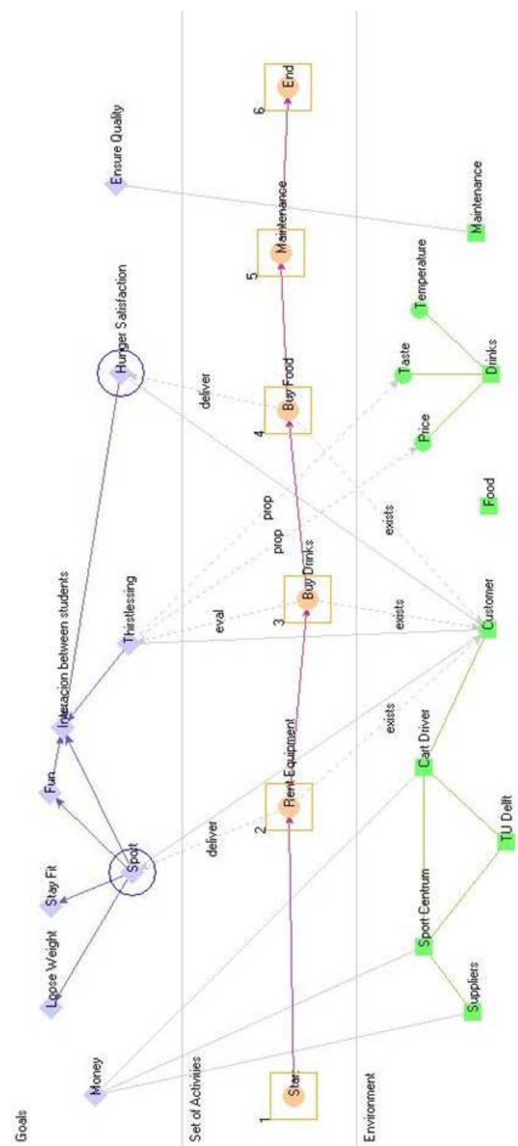

Fig. A.1. the PSS design concept under development at Project A

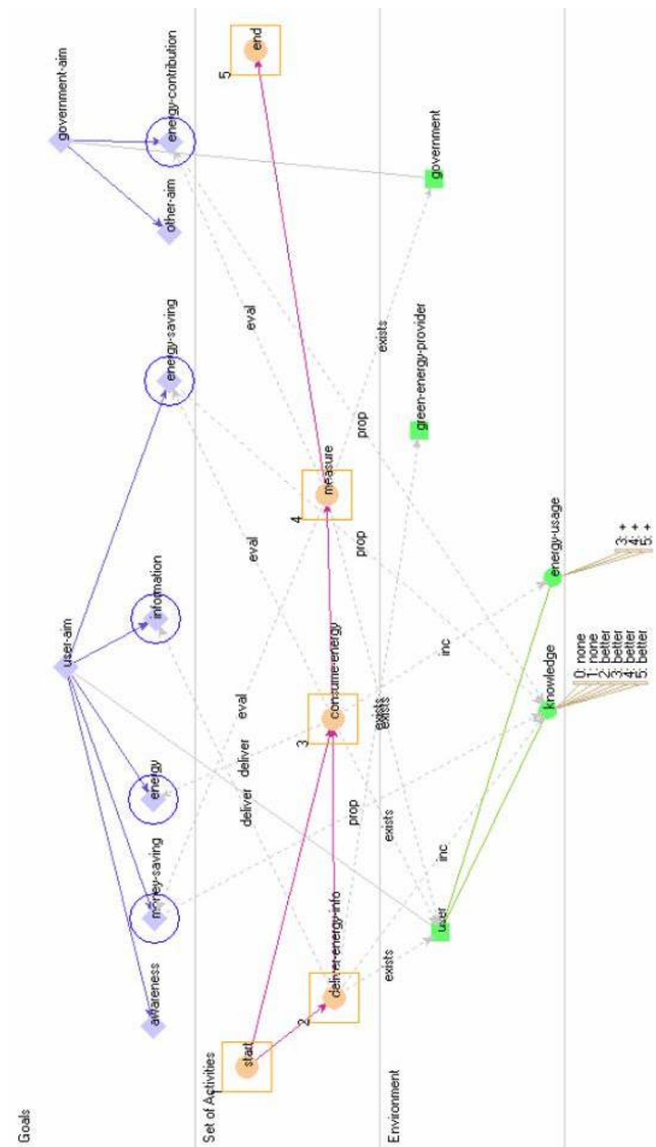

Fig. A.2. The PSS design concept under development at Project B

Project C Developing a repair service system for cyclists within the new Mekelpark

We used *Service CAD* to get an impression of the connection between the aims, activities and its environment. The program really forced us to think on what would and can happen to our concept. By looking first at what we would like to achieve with the service and then thinking about the activities that need to be done to get there, you really are focused on every step. It's a great program to make a fast and simple visualization of the service system that you're designing; we did not use the possibility to programming *Service CAD*, because in this case it would not help us to understand the service better. Although we know that engineering departments will use this basis to develop and finalize the system.

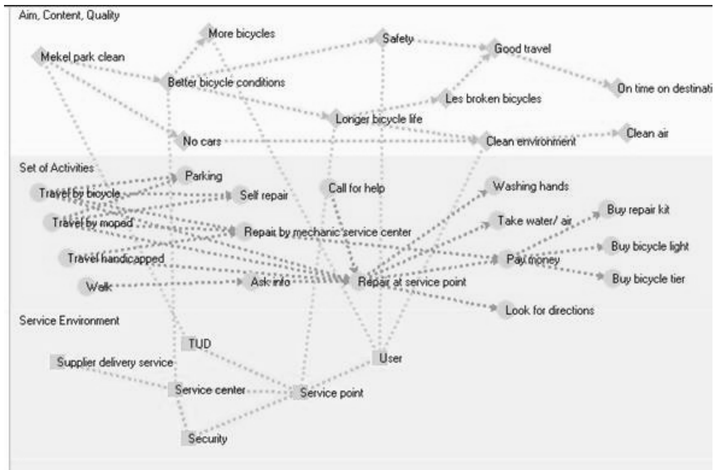

Fig. A.3. The PSS design concept under development at Project C

Project D: SymBioSys- How to make money out of waste in the Port of Rotterdam

The first tool we used was *Service CAD*. It can be helpful in the first stages of the PSS-design, as it supports the designer to identify all of the important factors that have influence on the performance of the PSS. The different stakeholders, actions and the goals were inserted and as good as possible connected. The problem with SymBioSys is that it can only be described in terms of examples, that will be different for every construction of connections SymBioSys will engage and on a global level, that does not give a lot of clarity. Therefore the level of implementation is different through the chart, as can be seen in the graphic. the goals and the environment stay quite abstract, while the activities are more specified. It would be helpful to integrate the possibility of showing the same PSS on different levels of abstractness. Problems with the program were encountered where it came to actual programming of connections, as this was nowhere to be found how to formulate the scripts. Nonetheless, *Service CAD* can be a helpful tool when used by a programmer at the right time in the design process.

Project E Transit: Trans-to-skate, Trans-to-drive - Providing eco-safe mobile services in the TU Delft Mekelpark

In the design process, *Service CAD* is used to assist concept generation, problem solution and evaluation. *Service CAD*, as a computer aided design tool for PSS design, aims to generate a system of products and services to satisfy the needs of customers. After conducting a S.W.O.T. analysis (Chapter 1.1.2) to realize the problems of the current situation and the opportunities of the future, we choose to focus on the transportation of TU Delft people without their own transportation tool, but who still need to move around different buildings in one day.

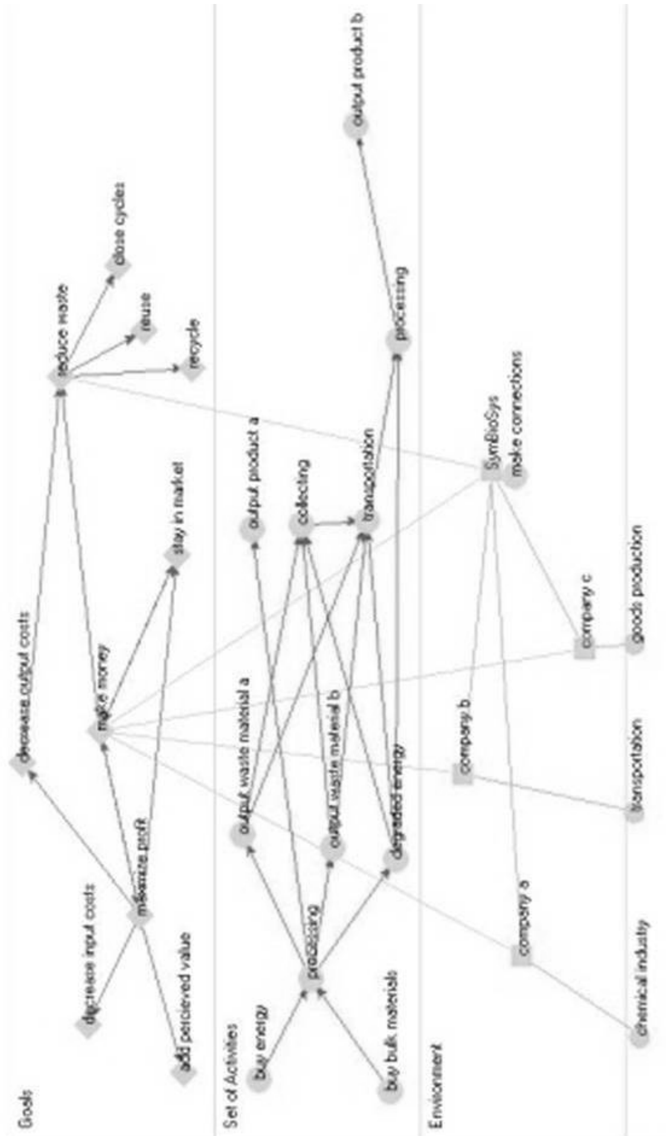

Fig. A.4 The PSS design concept under development at Project D

Table A.2 Elements of the PSS design concept at Project E

Stakeholders	In the TRANSIT service system, there are 5 stakeholders, commuters/visitors, TU Delft, Manufacturer, Sponsor, and Bank. The first is the service receiver; TU Delft is the service provider. Manufacturer, Sponsor, and Bank are involved in the B2B with TU Delft.
Service goal and quality	As the whole service system is constructed and run on the basis of satisfying each stakeholder's need, the first step is to analyze the need carefully from economic environmental and socio-cultural perspective. In regard with the service receivers, the goal is to improve their transportation experience within the TU Delft campus. The service receivers are the long-time users (students and employees), who are called commuters in campus, and short-time users (visitors). The graph below is what we did in *Service CAD* of the needs of commuters and visitors. The total experience of delft mobility can be divided into 5 parts, namely, comfort, safety, convenience, efficiency, and economic aspects, such as affordability. For a service provider, TU Delft needs a reliable system, safe and efficient, and a long-term stable service cycle. This system should also provide added value, such as improving the satisfaction and trust of students and building up good fame of attention on sustainability. For the other stakeholders as far as the B2B activities are concerned, the added value is mainly about economic perspective, profitability and business development.
Activities and service environment	For the service receivers, the activities are shown in the graphs below. For each activity, the service is integrated to meet the needs of the users. The quality of the service is evaluated by the users on the basis of service environment at the same time.

Project F Mobility-service for the Mekelpark

To control and asses our PSS we also used *Service CAD*. *Service CAD* has been used to map the whole system and to see if the whole system will work. With *Service CAD*, by Komoto, aims, actions and qualities, and also actors can be mapped. With the whole new system, a simulation is runned, in order to test if there are any vacancies in the system design. In this case, it was used in the elaboration phase of the product service system, to check if every aspect of the system was covered. However the results were not satisfactory to us. We were not able to provide the necessary data that was required to test the system in *Service CAD*. This project at this level was not suitable for using *Service CAD*. If it had been a project that would reach a stage of implementation, describing all the factors and stakeholders thoroughly this system would be a valuable tool to check if the system would function

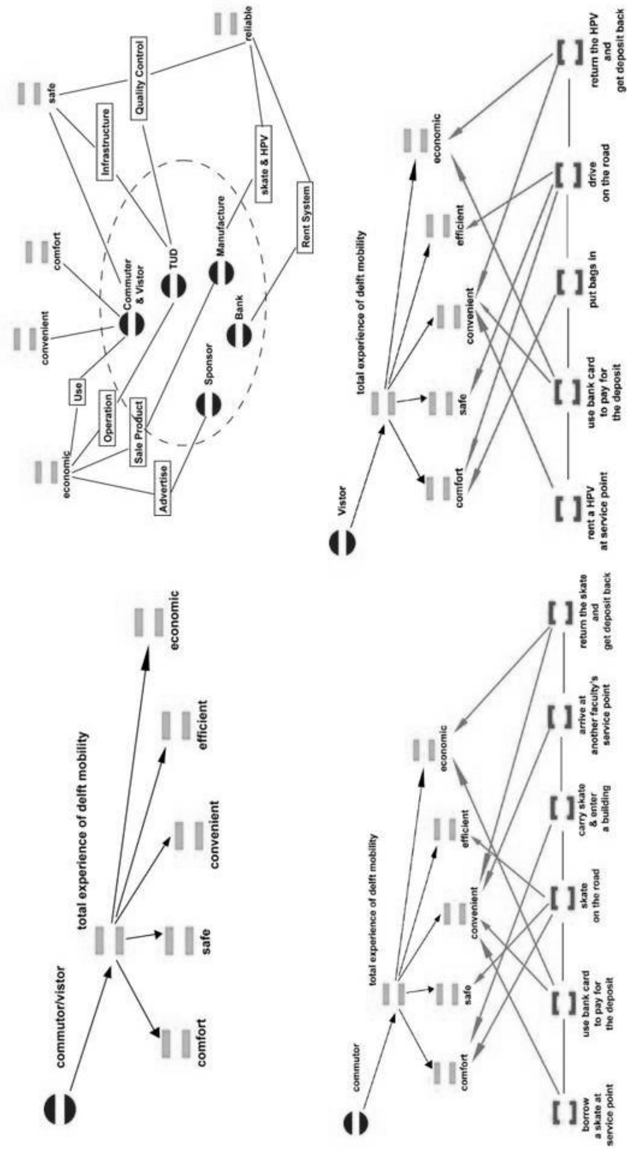

Fig. A.5 The PSS design concept under development at Project E

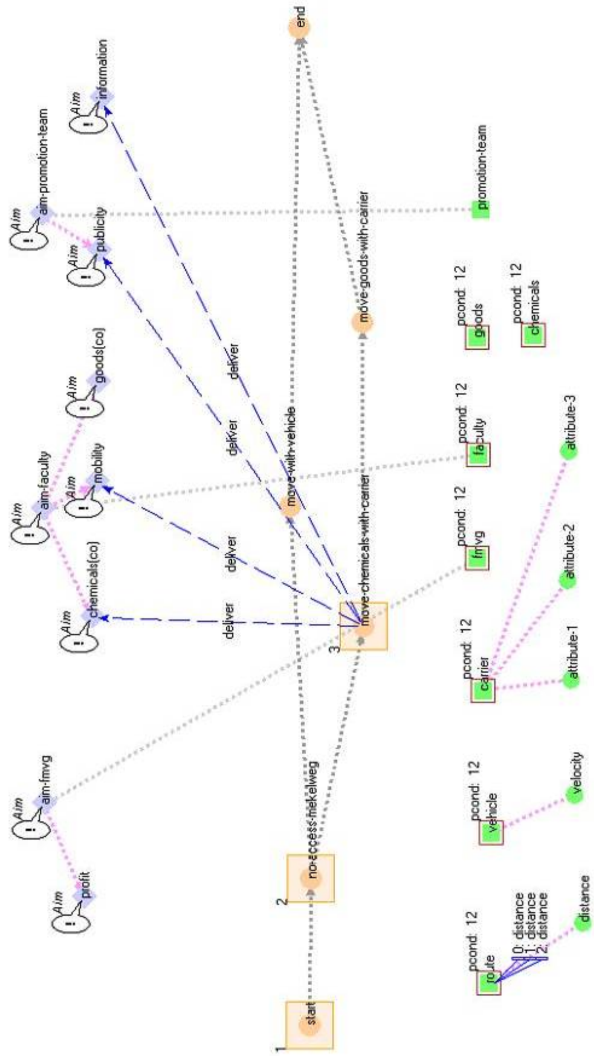

Fig. A.6 The PSS design concept under development at Project F

Project G Product-service systems: from idea to business plan: the Ameland bio-bus (also shown in Chapter 7)

Service CAD has been used during conceptual design by specifying service elements; goals of the service, design object i.e. service and service environment and their relationships for the Ameland bio-bus PSS. There are two main stakeholders, tourist and inhabitants of Ameland in the PSS. The service elements are summarized in the table below.

Service CAD has been used to verify configurability of PSS from economic and delivery performance perspective. The tool provided us with complete overview of various service events and interaction between different service elements. However, the verification of the service at various stages where different stake holders interact with each other was hard to determine. The tool helped us determine whether the existing service elements were able to satisfy the goal of PSS through reconfiguration and also in finding side effects in the PSS design. In future, this tool would help to support design and evaluation of sustainable PSS through combining both qualitative and quantitative evaluation methods

Table A.3 Elements of the PSS design concept in Project G

Service Goal	Tourist goal, Inhabitant goal, Information, Food supply, Cost, flexibility
Service Quality	Mainland mobility, Waddensea, mobility, Heavy mobility, Accommodation, Energy
Service body as activities	Transport to port, Transport inside Ameland, Stay/leave at holiday house, Collection of bio waste, Transport of bio waste,
Service receivers and providers	Tourists, ferry, restaurants, bio-bus, bio-gas-factory, holiday house, inhabitants, supermarkets

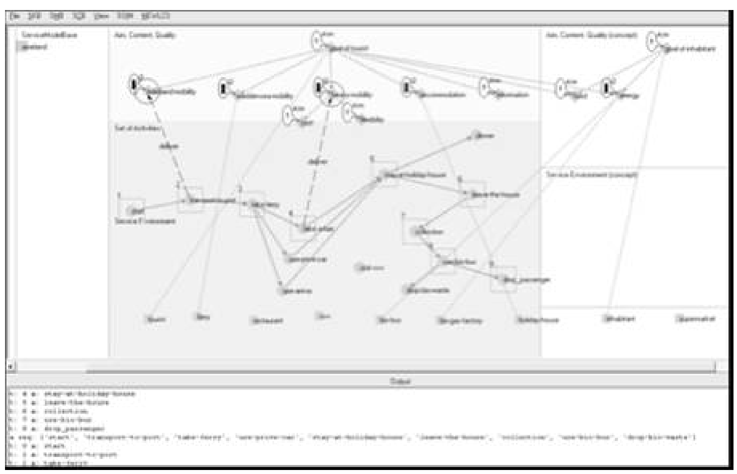

Fig. A.7. The PSS design concept under development at Project G (This figure is as same as Fig. 7.5)

Appendix B: Terminology

- **CAD tools:** Computer aided design tools to support product design.
- **CAD/CAE tools:** Computer aided design and engineering tools to support product design integrated with numeric performance evaluation modules.
- **Functional CAD tools:** CAD tools that utilize function information as design specification to support product design. An examples of functional CAD tools is the FBS modeler (Umeda et al. 2005)
- **Geometric CAD tools:** CAD tools dedicated to support product design in terms of geometry.
- **Geometric model:** A product model manipulated on geometric CAD tools.
- ***ISCL*:** A prototype CAD/CAE tool to support systematic PSS design concept generation and probabilistic and quantitative PSS design concept evaluation. *ISCL* is named after an **I**ntegration of a **S**ervice **C**AD and a **L**ife cycle simulator. This tool is developed in this study to answer the research questions. The mechanism of the tool is described in Chapter 4.
- **Life cycle simulator:** A CAE tool to evaluate the performances of a life cycle of products using life cycle simulation technique. Life cycle simulation technique is described in Section 2.1.2. A life cycle simulator is included in *ISCL*. The mechanism of the life cycle simulator is described in Chapter 4.
- **Service:** a set of activities to deliver contents from providers to receivers with channels in environment. (Tomiyama et al. 2004). This definition implies that service should be explained with other types of design information.
- ***Service CAD*:** A prototype CAD tool to support systematic PSS design concept generation. This tool is developed in this study to answer the research questions. The mechanism of the tool is described in Chapter 3.
- **Service CAD tools:** CAD tools dedicated for service design. Recently the term is used to represent CAD tools to support integrated product-service offerings (Sakao and Rindaal 2009). Service CAD tools are also called service CAD systems (e.g., Arai and Shimomura 2004; 2005).
- **Product model:** A generic description of a product.
- **The Product Service System (PSS) concept:** A business modeling methodology, whose focus is on relationships between products and services so that they can jointly satisfy the needs of customers, while realizing sustainable production and consumption (Mont 2002).
- **Product Service Systems (PSSs):** Business models designed based on the PSS concept.
- **PSS design process:** Design process of Product Service Systems

- **PSS modeling:** A method to represent information about Product Service Systems. Definition of model elements included in a PSS modeling depends on the purpose of the modeling (see Chapter 2).
- **Service modeling:** A method to represent information about service and related concepts. Definition of service and types of concepts included in a service modeling depends on the purpose of the modeling (see Chapter 2).

References

Alonso-Rasgado MT, Thompson G, Dannemark OJ (2004) State of the art in service design and modeling, VIVACE Consortium Monograph

Amini SH, Remmerswaal JAM, Castro MB, Reuter MA (2007) Quantifying the quality loss and re source efficiency of recycling by means of exergy analysis. Journal of Cleaner Production 15:907-913.

Arai T, Shimomura Y (2004) Proposal of Service CAD System - A Tool for Service Engineering, Annals of the CIRP 53(1):397-400.

Arai T, Shimomura Y (2005) Service CAD System - Evaluation and Quantification, Annals of the CIRP 54(1):463-466.

Bakiri R (2003) Towards a new service design approach assisted by computer tools: a typology of services and a post sale service case study in the automotive industry. In Proceedings of International Conference Systems, Man and Cybernetics, Vol. 4, 2003. IEEE, pp. 3899-3904.

Bakker H (2002) Ontstaan en groei van de recreatie of Ameland, VVV Ameland.

Bayindir, Z.P., Dekker, R., Porras, E., 2006. Determination of recovery for a probabilistic recovery system under various inventory control policies. Omega, 34:571-584.

Bartolomeo M, dal Maso D, de Jong P, Eder P, Groenewegen P, Hopkinson P, James P, Nijhuis L, Örninge M, Scholl G et al. (2002) Eco-efficient producer services—what are they, how do they benefit customers and the environment and how likely are they to develop and be extensively utilized? Journal of Cleaner Production 10(3):829-837.

Berchicci L (2005) The green Entrepreneur’s challenge. PhD Thesis, Delft University of Technology, Delft, the Netherlands.

Berkley BJ (1996) Analyzing service blueprints using phase distributions, European Journal of Operational Research 88:152-164

Botta-Genoulaz, V., Millet, P.,-A., Grabot, B, 2005. A survey on the recent research literature on ERP systems. Computers in Industry, 56, 510-22.

Bracewell RH and Sharpe JEE (1996) Functional Descriptions Used in Computer Support for Qualitative Scheme Generation—Schemebuilder, Artificial Intelligence for Engineering Design, Analysis and Manufacturing: AIEDAM. 10:333–346.

Brezet H, Bijma SA, Silvester S (2001) The design of eco-efficient services: Method, tools and review of the case study based ‘Designing Eco-Efficient Services’ project Design for sustainability program, Delft University of Technology, Delft, The Netherlands.

Castro B (2005) Design for resource efficiency – Preserving the quality in the (automobile) resource cycles. PhD Thesis, Delft University of Technology, Delft, the Netherlands.

CBS (2007) Centraal Bureau voor de Statistiek, (www.cbs.nl), visited in 2007.

Chai KH, Zhang J, Tan KC (2005) A TRIZ-Based Method for New Service Design, Journals of Service Research 8(1):48-66

Chandrasekaran B (2005) Representing function: relating functional representation and functional modelling research streams, Artificial Intelligence for Engineering Design, Analysis and Manufacturing: AIEDAM. 19:65-74

Chang HT, Chen JL (2004) The conflict-problem-solving CAD software integrating TRIZ into eco-innovation, Advances in engineering software 35:553-566

Chouinard M, D'Amours S, Ait-Kadi D (2008). A stochastic programming approach for designing supply loops. International Journals of Production Economics, 113, 657-677.

CIRP, College International pour la Recherche en Productique (the International Academy for Production Sciences). (www.cirp.org) visited on October 2008.

Clark G, Johnston R, Shulver M (2000) Exploring the service concept for service design and development, In: Fitzsimmons J, Fitzsimmons M (Eds.), New Service Design. Sage, Thousand Oaks, CP pp.71-91.

Coello Coello CA, van Veldhuizen DA, Lamont GB (2002) Evolutionary Algorithms for Solving Multi-Objective Problems. Springer.

De Amelander 2008(11) ISSN 0927-3565.

De Kleer J, Brown JS (1984) A qualitative physics based on confluences, Artificial Intelligence 24(3):7-83

Dolnicar S, Leisch F (2008) Selective marketing for environmentally sustainable tourism, Tourism Management (29) pp.672-680.

Dujairaj SK, Ong SK, Nee AYC, Tan RBH (2002). Evaluation of Life Cycle Cost Analysis Methodologies. Corporate Environmental Strategy, 9(1):30-39.

Edvardsson B, Olsson J (1996) Key concepts of new service development, The service industries journal 16:140-164.

Eger AO (2007) Evolutionaire productontwikkeling. Lemma. ISBN 978-90-5931-054-4. (English site: www.evolutionaryproductdevelopment.org/wiki/ visited in June 2009).

Ehrenfeid JR (2008) Sustainability by Design, Yale University Press, ISBN 978-0-300-13749-1.

Erden MS, Komoto H, Van Beek TJ, D'amelio V, Echavarria E, Tomiyama T (2008) A review of function modeling: Approaches and applications, Artificial Intelligence for Engineering Design, Analysis and Manufacturing: AIEDAM. 22:147-169

Erol P, Thoeming J (2005) Eco-design of reuse and recycling network by multi- objective optimization, Journal of Cleaner Production 13:1449-1460.

Far BH, Elamy AH (2005) Functional reasoning theories: problems and perspectives, Artificial Intelligence for Engineering Design, Analysis and Manufacturing: AIEDAM. 19:75-88

Fadeeva, Z (2005) Translation of sustainability ideas in tourism networks: Some roles of cross-sectional networks in change towards sustainable development, Journal of Cleaner Production (13) pp. 175-189.

Fandel G, Stammen M (2004) A general model for extended strategic supply chain management with emphasis on product life cycles including development and recycling. International journal of production economics, 89:293-308.

Fleischmann M, Jacqueline MBR, Dekker R, van der Laan E, van Nunen JAEE, van Wassenhove LN (1997). Quantitative models for reverse logistics: A review. European Journals of Operational Research, 103:1-17.

Fonseca CM, Fleming, PJ (1993) Genetic Algorithms for Multi-objective Optimization: Formulation, Discussion and Generalization. In: Proceedings of the Fifth International Conference on Genetic Algorithms, Morgan Kauffman, San Mateo, California, 416-423.

Forbus KD (1984) Qualitative process theory, Artificial Intelligence 24(3):85-168

Forbus KD, de Kleer J (1993) Building Problem Solvers, MIT Press.

Fujimoto J, Umeda Y, Tamura T, Tomiyama T, Kimura F (2003) Development of Service-Oriented Products Based on the Inverse Manufacturing Concept. Environmental Science & Technology, 37 (23):5398-5406.

Geogiadis, P., Vlachos, D., 2004. The effect of environmental parameters on product recovery. European Journals of Operational Research, 157, 449-464.

Goldstein SM, Johnston R, Duffy JA, Rao J (2002) The service concept: the missing link in service design research? Journal of Operations Management 34:121-134

Graedel TE, Allenby BR (2003) Industrial ecology, New Jersey (USA), Pearson Education Press

Goedkoop MJ, van Halen CJG, te Riele HRM, Rommens PJM, Product Service Systems, Ecological and Economic Basics", Pre consultants, (www.pre.nl)

Hara T, Arai T, Shimomura Y (2006) Development of a Service Logical Model based on the Concept of Serviset. Design Shimposium Koen Ronbunshu (in Japanese), pp. 187-192.

Hata T, Kimura F, Suzuki H. (1997). Product life cycle design based on deterioration simulation. In Life Cycle Networks, (Krause, F-L. and Seliger, G., Eds.), pp. 197-206. Chapman & Hall, London.

Hata T, Kato S, Sakamoto H, Kimura F, Suzuki H (2000) Product Life Cycle Simulation with Quality Model. Proceeding of 7th CIRP International Seminar on Life Cycle Engineering, pp.60-67.

Hill AV, Collier DA, Froehle CM, Goodale JC, Metters RD, Verma R (2002) Research opportunities in service process design, Journal of Operations Management 20:189-202

Hugo A, Pistikopoulos EN, (2005) Environmentally conscious long-range planning and design of supply chain networks. Journal of Cleaner Production 13:1471-91.

Iacobucci D, Grisaffe D, Duhachek A, Marcati A (2003) FAC-SEM: A Methodology for Modelling Factorial Structural Equations Models, Applied to Cross-Cultural and Cross-Industry Drivers of Customer Evaluations, Journals of Service Research 6(1):3-23

Inskeep E (1987) Environmental planning for tourism. Annals of Tourism Research 14:118-135.

Johansen M, Umeda Y, Tomiyama T (1997) Life Cycle Simulation for Verifying Sustainable Model of Products. In: L.M. Camarinha-Motos (ed.): Re-Engineering for Sustainable Industrial Production, Chapman & Hall, London, pp. 247-258.

Jorysz HR, Vernadat FB (1990) CIM-OSA Part 1: total enterprise modelling and function view, International Journal of Computer Integrated Manufacturing 3(3):144-156

Jorysz HR, Vernadat FB (1990) CIM-OSA Part 2: information view, International Journal of Computer Integrated Manufacturing 3(3):157-167

Hanssen OJ (1999) Sustainable product systems-experiences based on case projects in sustainable product development. Journal of Cleaner Production 7(1):27-41.

Hatamura Y (1993) The practice of machine design. In: Design and CAD, Kimura F. Yoshikawa H. (eds.), Asakura Shoten (in Japanese).

Hertwich EG, Perse WS, Koshland CP (1997) Evaluating the environmental impact of products and production processes: a comparison of six methods. the Science of the Total Environment, 7(196):13-29.

Hopman H (2007) Innovation-Focused Ship Design Developments and options from a European perspective. In: Proceedings of Delft Science in Design 2. Platform Design, Delft.

Ignatenko O, van Schaik A, Reuter MA (2008) Recycling system flexibility: the fundamental solution to achieve high energy and material recovery quota. Journal of Cleaner Production 16:432-449.

Kandelaars PPAAH, van den Bergh JCJM (1997) Dynamic analysis of materials-product chains: An application to window frames. Ecological Economics, 22:41-61.

Kato S, Kimura F (2004) The Product Life Cycle Design Method using a Strategic Analysis. 11th International CIRP Life Cycle Engineering Seminar “Product Life Cycle – Quality Management Issues”, Belgrade, Serbia.

Karni R, Arciszewski T (1998) A design tool for the conceptual design of production and operations systems. Research in Engineering Design 9:146-167

Kernel P (2005) Creating and implementing a model for sustainable development in tourism enterprises. Journal of Cleaner Production 13:151-164.

Khan FI, Sadiq R et al. (2004) Life cycle iNdeX (LInX): a new indexing procedure for process and product design and decision-making. Journal of Cleaner Production 12(1):59-76.

Kheir NA (1995) Systems Modeling and Computer Simulation. Dekker, ISBN 0-8247-9421-4

Krikke H, Bloemhof-ruwaard, van Wassenhove LN () Concurrent product and closed-loop supply chain design with an application to refrigerators. Int. J. Prod. Res. 41(16):3689-3719.

Kobayashi H (2005) Strategic evolution of eco-products: a product life cycle planning methodology. Research in Engineering Design, 16:1-16.

Kobayashi H (2006). A systematic approach to eco-innovative product design based on life cycle planning. Advanced Engineering Informatics, 20:113-125.

Komoto H, Tomiyama T, Nagel MH, Silvester S, Brezet H (2005) A multi-objective reconfiguration method of supply chains through discrete event simulation. In: Proceedings of EcoDesign 2005: 4th International Symposium on Environmentally Conscious Design and Inverse Manufacturing. Piscataway: IEEE. 320-325.

Komoto H, Tomiyama T, Nagel M, Slivester S, Brezet H (2005) Life Cycle Simulation for Analyzing Product Service Systems, 4th International Symposium on Environmentally Conscious Design and Inverse Manufacturing (EcoDesign 2005), IEEE, 386-393.

Komoto H, Tomiyama T (2008) Integration of a Service CAD and a Life Cycle Simulator, Annals of the CIRP 57(1):9-12.

Kondoh S, Soma M, Umeda Y (2005) Simulation of closed-loop manufacturing systems focused on material balance of forward and inverse flows. International Journal of Environmental Conscious Design and Manufacturing, 13 (2).

Krozer J, Christensen-Redzepovic E., Sustainable innovation at tourism destination (working paper)

Kuo NW, Hsiao TY, Yu YH (2005) A Delphi-matrix approach to SEA and its application within the tourism sector in Taiwan, Environmental Impact Assessment Review (22) pp.259-280.

Kumazawa T, Kobayashi H (2006) A simulation system to support the establishment of circulated business. Advanced Engineering Informatics, 20:127-36.

Levin DC, Rao VM, Parker L, Frangos AJ, Sunshine JH (2008) Ownership or Leasing of MRI Facilities by Nonradiologist Physicians Is a Repidly Growing Trend. American College of Radiology DOI 10.1016/j.jacr.2007.09.017.

Lovelock CH, Wright L (1999) Principles of Service Management and Marketing, Prentice-Hall, Englewood Cliffs, NJ

Marca DA, Miorgan CL (1998) Structured Analysis and Design Technique, McGraw-Hill, Inc. New York, NY, USA

Masaoka K, Sakao T, Umeda Y, Tomiyama T (1996) Verification of the Post Mass Production Paradigm by Simulation. In: Proceedings of Annual Spring Conference of Japanese Society for Precision Engineering, 2 pages (in Japanese).

Maxwell D, van der Vorstb R (2004) Developing sustainable products and services. Journal of Cleaner Production 11:883-895.

Mendivil R, Fischer U, Hungerbuehler K (2005) Impact of technological development, market and environmental regulations on the past and future performance of chemical processes. Journal of Cleaner Production, 13:869-880.

Michelini RC, Razzoli RP (2004) Product-service eco-design: Knowledge-based infrastructures. Journal of Cleaner Production, 12:415-428.

Mont O (2002) Clarifying the Concept of Product Service Systems, Journal of Cleaner Production, 10(3):237-245

Mont O, (2004) Institutionalisation of sustainable consumption patterns based on shared use. Ecological Economics, 50(1-2):135-153.

Nagel MH (2001) Environmental Quality in the Supply Chain of an Original Equipment Manufacturer in the Electronics Industry; Research, Development, Evaluation, Validation and Implementation of Environmental Performance Tools in the Scope of Total Cost of Ownership. Ph.D. study, Delft University of Technology, ISBN 90-9015022-6.

Nagel M, Komoto H, Tomiyama T, Silvester S, Brezet JC (2005) Environmental and Economical Aspects of Reconfigurable Supply Chain Management. In: 3rd Proceedings of International Conference on Reconfigurable Manufacturing, Ann Arbor, Michingan, May 10-12.

Nijkamp P, van den Bergh JCLM (1997) New advances in economic modelling and evaluation of environmental issues. European Journals of Operational Research, 99, 180-96.

Pahl G, Beitz W (1996) Engineering Design: A Systematic Approach, 2nd ed., Springer-Verlag, London, Great Britain.

Robinson S (2002) General concepts of quality for discrete event simulation. European Journal of Operational Research, 138:103-117

RoHS, EU Directive 2002/95/EC, 2002. Restriction of the Use of Certain hazardous Substances in Electrical and Electronic Equipment (RoHS).

Ross TD, Rodriguez (1963) Theoretical Foundation of Computer-Aided Design System, Proceedings of the 1963 Spring Joint Computer Conference, Spartan Books, pp. 305-322.

Ross TD, Schoman KE (1977) Structured Analysis for Requirements Definition. IEEE Transactions on software engineering, 3(1):6-15

Sander PC, Brombacher AC (2000) Analysis of quality information flow in the product creation process of high-volume consumer products. International journal of production economics, 67:37-52.

Sakai N, Tanaka G, Shimomura Y (2003) Product Life Cycle Design Based on Product Life Control. Environmentally Conscious Design and Inverse Manufacturing, Proceedings. EcoDesign '03, IEEE, pp. 102-108.

Sakao T, Shimomura Y (2007) Service Engineering: a Novel Engineering Discipline for Producers to Increase Value Combining Service and Product, Journal of Cleaner Production, 15:590-604.

Schwarz HG (2006) Economic materials-product chain models: Current status, further development and an illustrative example. Ecological Economics, 58, 373-92.

SCORE! Sustainable Consumption Research Exchange (www.score-network.org) visited in October 2008.

Senthil KD, Ong SK, Nee AYC, Tan RBH (2003) A proposed tool to integrate environmental and economical assessments of products. Environmental Impact Assessment Review, 23, 51-72.

Shimomura Y, Watanabe K, Arai T, Sakao T, Tomiyama, T (2003) A proposal for servcie modelling. 3rd International Symposium on Environmentally Conscious Design and Inverse Manufacturing (EcoDesign 2003), IEEE, pp. 75-80.

Shimomura Y, Umeda Y, A Proposal of Upgrade Design. Environmentally Conscious Design and Inverse Manufacturing, 1999. Proceedings. EcoDesign '99, IEEE, pp. 1000-1004.

Shostack GL (1981) How to Design a Service. European Journal of Marketing 16(1): 49-63.

Shu LH, Wallace DR, Flowers WC (1996) Probabilistic Methods in Life-Cycle Design, In: Proceedings of IEEE International Symposium on Electronics and the Environment, Dallas, TX, pp. 7-12.

Sistrom CL, McKey NL (2005) Costs, Charges, and Revenues for Hospital Diagnostic Imaging Procedures: Differences by Modality and Hospital Characteristics American College of Radiology DOI 10.1016/j.jacr.2004.09.013.

Sousa RD, Ying ZZ, Yang LC (1998) Modelling business processes and enterprise activities at the knowledge level, AIEDAM 12:29-42

Stevels A (2000) Five ways to Make Money While Being Green, Proceedings of the 7th CIRP International Seminar on Life Cycle Engineering.

Suspronet, the EU's first Thematic Network on Product Service Development (www.suspronet.org) visited in October 2008

Sundin E, Bjorkman M, Jacobsson N (2000) Analysis of service selling and design for remanufacturing, Int. Symposium on Electronics and the Environment, 2000, IEEE, pp. 272-277.

Sundin E, Bras B (2005) Making functional sales environmentally and economically beneficial through product remanufacturing, Journal of Cleaner Production 13(9):913-925.

Sutherland IE (1963) Sketchpad: A Man-Machine Graphical Communication System. Technical Report No. 296, Lincoln Laboratory, Massachusetts Institute of Technology via Defense Technical Information Center

Takata S, Yamada A, Kohda T, Asama H (1998) Life Cycle Simulation Applied to a Robot Manipulator - An Example of Aging Simulation of Manufacturing Facilities -, Annals of the CIRP 47(1):397-400.

Takata S, Ogawa T, Umeda Y, Inamura T (2003) "Framework for systematic evaluation of life cycle strategy by means of life cycle simulation," in Proceedings of the Third International Symposium on Environmentally Conscious Design and Inverse Manufacturing (EcoDesign03), IEEE, 2003, pp. 198-205.

Takeda H, Tomiyama T, Yoshikawa H, Veerkamp PJ (1990) Modeling design process. Centrum voor Wiskunde en Informatica, Report CS-R9059.

Tojo N (2004) Extended Producer Responsibility as a Design Change, Dissertation, International Institute of Industrial Environmental Economics, Lund University, Sweden.

Tomiyama T, Umeda Y, Yoshikawa H (1993) A CAD for functional design, Annals of the CIRP, 42(1):143-146

Tomiyama T (1997) A Manufacturing Paradigm Toward the 21st century. Integrated Computer Aided Engineering. 4:159-178

Tomiyama T (2001) Service Engineering to Intensify Service Contents in Product Life Cycles. 2nd International Symposium on Environmentally Conscious Design and Inverse Manufacturing (EcoDesign 2001), IEEE, pp. 613-618.

Tomiyama T (2002) Service Engineering to Intensify Service Contents in Product Life Cycles. ECP News Letter, No.19, Japan Environmental Management Association For Industry.

Tomiyama T (2002) Design theory. ISBN 4-00-01-995, Iwanami Shoten (in Japanese).

Tomiyama T, Meijer BR (2003) Service CAD. In: Proceedings the SusProNet Launch Conference, June 5-6, 2003, Amsterdam, SusProNet Project (http://www.suspronet.org), pp 69–71

Tomiyama T, Shimomura Y, Watanabe K (2004) A Note on Service Design Methodology. Proc. of DETC'04, ASME, 57393

Tukker A, Tischner U (2006) New Business for Old Europe, Gleenleaf Publishing, Sheffield

Umeda Y, Ishii M, Yoshioka M, Shimomura Y, Tomiyama T (1996) Supporting conceptual design based on the function-behavior-state modeller, Artificial Intelligence for Engineering Design, Analysis and Manufacturing: AIEDAM. 10(4):275-288

Umeda Y, Tomiyama T (1997) Functional reasoning in design. IEEE Expert 12(2):42-48

Umeda, Y., Nonomura, A., Tomiyama, T., 2000. Study on life-cycle design for the post mass production paradigm. Artificial Intelligence for Engineering Design, Analysis and Manufacturing, 14, 149-61.

Umeda, Y., 2001. Toward a life cycle design guideline for inverse manufacturing.

In: Proceedings of EcoDesign 2001: 2nd International Symposium on Environmentally Conscious Design and Inverse Manufacturing. Piscataway: IEEE. 143-148.

UNEP (2002) Product-Service Systems and Sustainability: Opportunity for sustainable solutions. (http://www.unep.fr/pc/sustain/reports/pss/pss-imp-7.pdf)

U.S. Air Force (1981) Integrated Computer-Aided Manufacturing (ICAM) Architecture Part II, Vol. IV-Function Modelling Manual (IDEF0) AFWAL-TR-81-4023, Air Force Materials Laboratory, Wright-Patterson AFB, Ohio 45433

van Schaik A, Reuter MA, Boin UMJ, Dalmijn WL (2002) Dynamic modelling and optimisation of the resource cycle of passenger vehicles. Minerals Engineering 15, 1001-1016.

Vogtlaender, J.G., Charles, F., Hendriks, C.F., Brezet, J.C., 2001, The EVR model for sustainability, The Journal of Sustainable Product Design, 1: 103–116.

VVV Ameland (2006) VVV GIDS 2006, Het Volk Printing.

VVV Ameland (2007) VVV GIDS 2007, Het Volk Printing.

Wang G, Huang SH, Dismukes JP (2004) Product-driven supply chain selection using integrated multi-criteria decision making methodology. International journal of production economics, 91:1-15.

WBCSD (2000) Eco-Efficiency: Creating more value with less impact. World Business Council for Sustainable Development.

WEEE, EU Directive 2002/96/EC, 2002. Waste Electrical and Electronic Equipment (WEEE)

Welch RV, Dixon DR (1994) Guiding Conceptual Design Through Behavioral Reasoning, Research in Engineering Design 6:169-188.

Williams A (2007) Product service systems in the automobile industry: contribution to system innovation? Journal of Cleaner Production 15:1093-1103.

Xiang Z, Formica S, Mapping environmental change in tourism: A study of the incentive travel industry, Tourism Management (28) pp.1193-1202

Yoshioka M, Umeda Y, Takeda H, Shimomura Y, Nomaguchi Y, Tomiyama T (2004) Physical concept ontology for the knowledge intensive engineering framework, Advanced Engineering Informatics 18:95-113

Yu S, Kato S, Kimura F (2001) Ecodesign for product variety: a multi-objective optimization framework, Environmentally Conscious Design and Inverse Manufacturing. Proceedings. EcoDesign '01, IEEE, pp. 293-298.

Summary in Dutch (Samenvatting)

In de twintigste eeuw domineerde het paradigma van massaproductie en massaconsumptie de economie. Dit heeft tot verschillende problemen in het milieu geleid, zoals opwarming van de aarde, het opraken van natuurlijke grondstoffen, watervervuiling, luchtvervuiling en moeilijk te verwerken industrieel afval. Aan het eind van de twintigste eeuw hebben onderzoekers methoden en tools ontwikkeld (EcoDesign) waarmee deze problemen vanuit het oogpunt van productontwerpen aangepakt konden worden. Echter, om te kunnen voldoen aan de eisen van onze maatschappij, is een verdere toename van eco-efficientie vereist. Dit betekent een verdere stijging in toegevoegde waarde van producten in combinatie met een afname van de milieuimpact. De integratie van productontwerp in het ontwerpen van diensten en andersom wordt verwacht te leiden tot efficiëntere en effectievere waardevermeerdering. Derhalve is, behalve de EcoDesign tools en methoden, een methodologie vereist om producten en diensten op systeem niveau te ontwerpen. Het op ontwerpmethodologie gebaseerde bedrijfsmodel dat zich op deze uitdaging richt, wordt product dienst combinatie ofwel 'Product Service System' concept genoemd. Het ontwerpproces dat gebruik maakt van het PSS concept wordt PSS ontwerpproces genoemd.

Computers zijn een van de uitvindingen die de economie in de twintigste eeuw hebben veranderd. Niet alleen zijn ze in staat om biljoenen gecompliceerde berekeningen te maken, ze helpen ook bij het uitvoeren van complexe intellectuele taken. Ontwerpen wordt gezien als een van deze complexe intellectuele taken, waarbij nieuwe kennis gegenereerd wordt over artefacten. Computer programmatuur om ontwerpers te ondersteunen bij het ontwerpen worden computer ondersteund ontwerp of 'computer aided design (CAD)' tools genoemd. Deze CAD tools zijn onderzocht en commercieel gebruikt om de productiviteit van het ontwerpproces en de kwaliteit van ontwerpoplossingen te verhogen. De verhoogde productiviteit en kwaliteit komen voort uit de mogelijkheid van CAD tools om ontwerpinformatie te gebruiken, op te slaan en uit te wisselen. De productiviteit en kwaliteit kunnen verder worden verbeterd door zogenaamde computer ondersteund engineering of 'computer aided engineering (CAE)' tools, die ontwerpoplossingen verifiëren en optimaliseren (meestal) met numerieke simulatie technieken.

Het doel van dit onderzoek is om CAD/CAE tools te ontwikkelen die gebruikt kunnen worden in het PSS ontwerpproces, opdat de productiviteit van het ontwerpproces en de kwaliteit van de ontwerpoplossing wordt verhoogd. Hiervoor worden kennis van het PSS concept en van CAD/CAE tools gecombineerd.

Binnen het kader van dit onderzoek stel ik ten eerste een systematische methode voor het ontwerpen van diensten, die gebaseerd is op het PSS concept, waarbij toegevoegde waarde vanuit een levenscyclus perspectief wordt gegenereerd. Om het ontwerpproces gebaseerd op de methode met berekeningen te ondersteunen beschouw ik vervolgens de formele eigenschap van ontwerpinformatie over producten, diensten en hun gerelateerde concepten zoals gebruikt in het ontwerpproces. Gebaseerd op deze beschouwing ontwikkel ik ten derde een prototype van een CAD/CAE tool om de ontwerpmethode te ondersteunen. Tenslotte analyseer ik de organisatie en het gebruik van deze ontwerpinformatie door middel van illustratieve voorbeelden voor verschillende ontwerptaken (bijv. in case studies).

In hoofdstuk 1 zijn achtergrond, kader, onderzoeksvragen, begrenzingen, procedure, overzicht en output van het onderzoek beschreven. Verder is het nut van dit onderzoek beschreven vanuit het perspectief van onderzoekers die de methoden en tools onderzoeken voor PSS ontwerp, van ontwerpers en ondernemers die te maken hebben met praktische ontwerpprojecten en van docenten die PSS ontwerp doceren en hun studenten.

In het PSS ontwerpproces zijn de diensten en levenscycli van de PSS de fundamentele elementen. In hoofdstuk 2 worden methoden om diensten en levenscycli te modeleren vanuit de literatuur besproken. Dit is nodig om CAD/CAE tools te ontwikkelen die gebruikt kunnen worden in het PSS ontwerpproces. Uit het literatuuronderzoek volgt de noodzaak voor een formele methode die ontwerpinformatie representeert die voorkomt in de bestaande methoden om diensten te modeleren. De literatuurstudie verduidelijkt verder de toepasselijkheid van het modeleren van levenscycli en simulatiemethoden voor kwantitatieve evaluatie van de prestaties van PSS.

Het eerste deel van hoofdstuk 3 is een afweging over de formele eigenschappen van producten, diensten en hun onderlinge relaties. De afweging betreft de karakteristiek van ontwerpen als intellectuele bezigheid die informatie definieert over artefacten om aan de gegeven eisen te voldoen. De afweging leidt tot een formele representatie van de ontwerpinformatie die gebruikt is in het PSS ontwerpproces. Het tweede deel van hoofdstuk 3 bestaat uit de structuur en het mechanisme van een prototype CAD tool voor PSS ontwerp, die in dit onderzoek `Service CAD’ genoemd wordt. De Service CAD ondersteunt het systematisch genereren van PSS ontwerpconcepten door gebruik te maken van ontwerpinformatie over producten en diensten die van tevoren is opgeslagen. Het laatste gedeelte van hoofdstuk 3 laat het proces zien van het genereren en voorbereiden van de ontwerpinformatie.

In hoofdstuk 4 wordt de integratie van de Service CAD met een levenscyclus simulator besproken. De integratie is een oplossing om de gebreken van de Service CAD te compenseren. Deze gebreken zijn het niet kunnen evalueren van kwantitatieve prestaties van de gegenereerde PSS ontwerpconcepten en het niet kunnen verwerken van ontwerpinformatie met een waarschijnlijkheidsvariabelen, zoals fysieke veroudering van producten en selectie van diensten door gebruikers. Nadat het mechanisme en de implementatie van de levenscyclus simulator zijn beschreven, wordt de integratie besproken. In dit onderzoek is de geïntegreerde tool aangeduid met ISCL.

Nadat het theoretische gedeelte is gepresenteerd, is de theorie toegepast in case studies. Deze case studies illustreren specifieke stadia in het PSS ontwerpproces waarin een kwantitatieve evaluatie van een PSS ontwerpconcept nodig is. Door ISCL in deze case studie te gebruiken, is de ontwerpinformatie die benodigd is voor het modeleren en evalueren van PSS ontwerpconcepten geanalyseerd.

De diensten binnen de levenscyclus van producten, waarop gefocussed is in sectie 5, zijn essentieel voor fabrikanten om toegevoegde waarde te genereren. Het soort diensten dat in dit hoofdstuk is beschreven omvat onderhoud aan producten en het opwaarderen van de functionaliteit van producten, die aangeboden zijn bij diverse contracten tussen gebruikers en fabrikanten (bijv. eigendomsoverdracht, gedeeld productgebruik en betaal-per-functie). Verder is het gedrag van gebruikers betreffende de keuze van diensten en de op prijs gebaseerde concurrentie in diensten tussen fabrikanten onderling beschouwd. Methoden om de diensten, de contracten en het gedrag van gebruikers te modeleren met ISCL zijn, samen met een analyse en vergelijking van de diensten, gepresenteerd door middel van resultaten van simulaties. De analyse verduidelijkt het soort ontwerpinformatie dat essentieel is in het ontwerpen van de integratie van de dienst.

Een PSS ontwerpproces voor fabrikanten bevat niet alleen het ontwerpen van diensten zoals beschreven in hoofdstuk 5, maar ook het ontwerpen van andere operaties binnen de levenscyclus van een product. In sectie 6 zijn deze operaties geanalyseerd met behulp van ISCL voor ‘original equipment manufacturers’ (OEMs). Het simulatiemodel van de ISCL definieert expliciet de relaties tussen operaties en hun aanvoerketens (bijv. het selecteren van leveranciers en het plaatsen van orders) en hun ‘end-of-life’ operaties (bijv. hergebruik en herfabricage). De uitkomst van de simulatie is gebruikt om de kwantitatieve impact van deze operaties op de prestaties van OEMs te evalueren vanuit meerdere doelen, zoals levenscycluskosten en milieuimpact. Zo een analyse die op simulaties gebaseerd is en is geïntegreerd met een optimalisatie naar meerdere doelen, is bruikbaar voor het evalueren van de effecten van operaties, om zich flexibel aan te kunnen passen aan nieuw geïntroduceerde milieuwetgeving en/of veranderde langetermijndoelen van de OEMs.

Het ontwerpen met PSS in de fabricagebranche kan anders zijn dan in de dienstenbranche. In sectie 7 is een toerisme-bedrijfsmodel voor duurzame doeleinden gebaseerd op het PSS concept geanalyseerd, als een voorbeeld van een PSS ontwikkelt vanuit de dienstverlening. In het bedrijfsmodel zijn diensten ontworpen rondom de activiteiten van gebruikers van producten. (bijv. toeristen) en producten zijn flexibel gekozen om te voldoen aan de behoeften van toeristen. Dit is in tegenstelling tot de bedrijfsmodellen die behandeld zijn in de hoofdstukken 5 en 6, die ontworpen zijn rondom de levenscyclus van producten. Dit hoofdstuk is bruikbaar voor het vergelijken van relevante ontwerpinformatie voor de fabricagebranche en in de dienstenbranche.

In hoofdstuk 8 zijn bevindingen van dit onderzoek samengevat, verkregen door het ontwikkelen van een prototype CAD/CAE tool voor PSS ontwerp en het gebruik van deze tool in verschillende PSS ontwerp case studies. Het soort essentiële ontwerpinformatie om PSS te modeleren en te evalueren zijn geidentificieerd. De bruikbaarheid en beperkingen van de CAD/CAE tools voor PSS ontwerpen worden besproken. Veranderingen in taken voor de PSS ontwerpers die gebruik maken van de CAD/CAE tools voor PSS ontwerp worden besproken. Verder zijn er aanbevelingen voor de ontwikkelaars en gebruikers van de CAD/CAE tools voor PSS ontwerp, en voor fabrikanten en ondernemers die in de praktijk te maken hebben met PSS ontwerp. Tot slot van dit onderzoek zijn commentaren van gebruikers van ISCL toegevoegd, die PSS ontwerpopdrachten hebben uitgevoerd met behulp van ISCL als onderdeel van een MSc programma aan de faculteit Industrieel Ontwerpen van de Technische Universiteit Delft.

Hitoshi Komoto, 2009

Summary in Japanese

大量消費・大量生産パラダイムに支えられた二十世紀の経済は、地球温暖化・原料枯渇・水質汚濁・大気汚染・過剰な廃棄物の発生など及ぶ多様な環境問題を残した。「エコデザイン」という概念は、これらの環境問題に製品設計の一観点から取り組むために導入された。そして、エコデザインに基づく設計方法論や設計支援ツール群が二十世紀後半に多く開発された。しかしながら、エコデザインに基づく製品設計改善のみでは、これらの環境問題への解決案（設計解）を環境効率という指標に基づいて社会が要求する水準を満たす提案することは難しい。このため、エコデザインに基づく設計方法論や設計支援ツール群のほかに、製品のライフサイクル内のサービス設計や製品とサービスの協調設計を行うための方法論、並びに支援ツール群が必要である。「Product Service System (PSS) コンセプト」と呼ばれる概念は、そのための一方法論を提供するものである。その方法論は「製品やサービスをシステム要素として扱い、（要素設計よりもむしろ）システム設計による環境効率の向上を目的とする」という言葉で特徴付けられる。この概念に基づいて設計されたビジネスモデルは PSS 事業と呼ばれ、例として、カーシェアリングなどが挙げられる。

コンピュータは二十世紀の経済に大きな影響を与えた発明のひとつである。それは膨大な単純計算を人間の代わりに行うのみならず、人間の高度な知的活動をも支援する。さて、「設計」とは人工物に関する知識を構築する、人間の高度な知的活動のひとつである。Computer Aided Design (CAD)ツール群はその知的活動をコンピュータの利用を通して支援するものである。CAD ツール群の具体的な機能は設計に用いられる情報の表現（可視化）・取得・選択・利用・保存・共有化などである。CAD ツール群の原型が発明され数十年が過ぎ、それらの開発のための継続的な研究活動とそれらの商品化により、製品設計過程の生産性及び設計された製品の質は飛躍的に向上した。さらに、数値計算やシミュレーションを用いて設計解を検証し最適化する Computer Aided Engineering (CAE)ツール群が研究・開発され、それらが CAD ツール群に統合されるようになった（CAD/CAE ツール群）。設計すべき人工物が複雑化する今日では、CAD/CAE ツール群はその設計支援のために不可欠である。

本研究は PSS コンセプトに関する研究と CAD/CAE ツール群に関する研究を俯瞰し、PSS コンセプトに基づく事業モデルの設計過程を支援する一 CAD/CAE ツールを提案するものである。そして、そのツールの利用を通して、PSS 事業の設計に用いられる情報がコンピュータ支援を受けることでどのように活用され得るかを理解するものである。

本研究は以下の４つの目標を持つ。先ず、製品ライフサイクル内において付加価値をもたらすサービスの設計を PSS コンセプトに基づいて系統的に行う一手法を提案する。その設計手法のコンピュータによる支援を可能にするために、製品・サー

ビス・それらの相互関係に関する設計情報の計算可能な表現方法を研究する。そしてその表現方法に基づいた一 CAD/CAE ツールを試作する。そのツールを幾つかの PSS 事業設計の例題で試用することで、PSS 事業の設計過程で用いられる設計情報のコンピュータ支援環境下における利用方法とその組織化に関して研究する。

本論分は八つの章で構成されている。第一章では本研究の背景、枠組み、研究課題、研究結果の適応範囲、研究方法、本研究の流れ、研究成果を述べる。また本論分の有用性を、設計手法や設計ツールの研究者・開発者、実際の PSS 設計事業に携わる設計者・企業家、PSS 事業の設計教育に携わる教育者・学生などの複数の観点から述べる。

PSS 事業の設計過程において、製品ライフサイクル内のサービスは PSS 事業を構築する基本的な要素である。そこで、第二章ではサービスと製品ライフサイクルのモデリング手法に関する類似研究を紹介する。これらの類似研究は PSS 事業の設計過程を支援する CAD/CAE ツール群が取り扱うべき設計情報の表現の形式化のための指針を与える。また、類似研究のうち、Life Cycle Simulation (LCS) 技術が PSS 事業を定量的に評価するために適していることを述べる。

第三章では最初に PSS 事業の設計過程で用いられる製品・サービス・それらの相互関係に関する情報の形式的な特性を研究する。この特性の研究にあたり、設計という知的活動に「仕様を満たすための人工物に関する情報を構築する過程」という定義を与える。この形式的な特性の研究に基づき、PSS 事業の設計過程における設計情報の形式的な一表現方法を提案する。また、この章では Service CAD と名付けた PSS 事業の設計過程を支援する CAD ツールの試作を提案する。Service CAD は PSS 事業の設計解生成過程を系統的に支援する機能を有する。この機能は PSS 事業の仕様に関する情報から PSS 事業内の製品・サービスに関する情報を導出することで達成される。このために、設計情報の提供者は設計情報を組織化された状態で Service CAD に与える。この章の後半部分では、PSS 事業を表現する設計情報の組織化の方法と設計解の生成過程を簡単な PSS 事業の設計例を用いて示す。

第四章では ISCL と名付けた Service CAD と LCS の統合ツールを、PSS 事業の設計で用いられる CAD/CAE ツールの試作として提案する。ISCL を利用することで Service CAD を用いて設計された PSS 事業の定量的評価が可能になる。とりわけ、LCS は PSS 事業内での製品の劣化や製品ユーザのサービスの選択などに関する不確実性を考慮するために必要である。また Service CAD と LCS の統合を実現するためには、両者間で用いられる設計情報の表現方法の対応を考慮する必要がある。この章では、ISCL に実装された LCS の構成を述べた後に、ISCL の構成、ISCL 上の設計情報の対応関係とその実装を示す。

第五章から第七章では PSS 事業の設計過程内での ISCL が果たすべき役割を幾つかの例題を通して分析する。とりわけ、その設計過程内で、PSS 事業の定量的評価・代替案との定量的比較が必要になる一工程での ISCL の利用に焦点をあてる。これらの例題内の PSS 事業に関する設計情報の分析を通して、PSS 事業の設計過程内における設計者の意思決定に必要な設計情報の種類を明らかにする。第五章では製品のライフサイクル内のサービス（メンテナンスやアップグレード等）、第六章では製品のライフサイクル内の製造活動と廃棄・再生活動（リユース・リマヌファクチュアリ

ング等）、第七章では（製造業に対して）サービス業が提供するサービスに関して利用される設計情報に焦点を当てる。

第八章では、コンピュータ支援環境下で PSS 事業の設計を行う場合の、設計情報の利用方法とその組織化に関してまとめる。最後に、PSS 事業の設計を支援する CAD/CAE ツール群の開発に関する将来の課題、PSS 事業の設計者全般とその設計教育に携わる教育者・学生への系統的な設計情報の利用に関する提言を行う。

高本仁志 2009

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Curriculum Vitae

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In 1995, Hitoshi Komoto graduated Kiyama Junior High School, Kiyama, Saga, Japan. In 1998, he graduated Sage-west Senior High School, Saga, Saga, Japan. In 1998, he enrolled the junior course at The University of Tokyo, Tokyo, Japan (Science I: majoring information physics and mathematical engineering).

After completing the junior course in 2000, he obtained a free one-way ticket to study mechanical engineering for four years at University of Karlsruhe (TH), Karlsruhe, Germany. During his stay in Karlsruhe, he completed a B.Sc and a Dipl.-Ing. in Mechanical Engineering at the university in 2003 and 2004, respectively. The title of Diplomarbeit was “Automatic Evaluation of Sensor Positions for Active Vision Systems with Application to Industrial Machine Vision”.

In 2004, he became a PhD candidate Delft University of Technology. The study described in this thesis has been carried out at this period. The study was supported by Cartesius Institute, a 3TU project.

In 2008, he became a researcher of Octopus project (system architecting of adaptable systems) at Delft University of Technology.