Elsevier Editorial System(tm) for Computers in Industry
Manuscript Draft

Manuscript Number: COMINDSI-D-11-00034

Title: Life Cycle Simulation for the Design of Product-Service Systems

Article Type: Product-Service System Engineering S.I.

Keywords: Life Cycle Simulation (LCS); Product-Service Systems (PSSs); Reference Architecture

Corresponding Author: Mr. Paolo Rosa,

Corresponding Author's Institution: Politecnico di Milano

First Author: Paolo Rosa

Order of Authors: Paolo Rosa; Marco Garetti, Full Professor; Sergio Terzi, Doctor

Abstract: The present paper discusses Life Cycle Simulation (LCS) as a new approach for supporting the design of PSSs (Product-Service Systems). The increased relevance of the life cycle perspective in the current society calls for more sustainable approaches to design, engineer and construct every-day products and related services. To answer to such a need, designers and engineers might have access to new methods and tools able to integrate in a proper way the life cycle perspective. In such a context, simulation - in its wider meaning - could play a relevant role for engineering the life cycle of a product and analyzing the related service networks. Within this context, the paper conducts a state of the art of existing approaches and solutions that support LCS, in order to identify common characteristics and prioritize next steps to be done for a comprehensive implementation. To this end a reference architecture is finally proposed.

Suggested Reviewers: Giuditta Pezzotta
giuditta.pezzotta@unibg.it
Life Cycle Simulation applied to Product-Service Systems is one of Dr. Pezzotta's research areas

Yoshiki Shimomura
yoshiki-shimomura@center.tmu.ac.jp
Life Cycle Simulation is one of Professor Shimomura's research areas

Opposed Reviewers:

Life Cycle Simulation for the Design of Product-Service Systems

Paolo Rosa, Marco Garetti
{paolo.rosa, marco.garetti}@polimi.it
Politecnico di Milano, Department of Management, Economics and Industrial Engineering
Piazza Leonardo da Vinci 32, 20133 Milano, Italy
Phone +39 02.2399.4760

Sergio Terzi*
sergio.terzi@unibg.it
Università degli Studi di Bergamo, Department of Industrial Engineering
Viale Marconi 5, 24044 Dalmine (Bergamo), Italy
Phone +39 035.2052.385
*Corresponding author

Abstract. The present paper discusses Life Cycle Simulation (LCS) as a new approach for supporting the design of PSSs (Product-Service Systems). The increased relevance of the life cycle perspective in the current society calls for more sustainable approaches to design, engineer and construct every-day products and related services. To answer to such a need, designers and engineers might have access to new methods and tools able to integrate in a proper way the life cycle perspective. In such a context, simulation – in its wider meaning – could play a relevant role for engineering the life cycle of a product and analyzing the related service networks. Within this context, the paper conducts a state of the art of existing approaches and solutions that support LCS, in order to identify common characteristics and prioritize next steps to be done for a comprehensive implementation. To this end a reference architecture is finally proposed.

Keywords: Life Cycle Simulation (LCS), Product-Service Systems (PSSs), Reference Architecture

1 Introduction

The modern world is affected by an intrinsic limit of sustainability. The current business models are based on a continuous cycle of production / consumption / dismission, pushed by the global competition, in which companies can survive only providing new products and new solutions for satisfying a growing demand. The limits and the weaknesses of this model have been already addressed and highlighted in many occasions, starting more than 20 years ago (e.g. the well-know and often-cited United Nations Brundtland Commission, debated in 1987). Fortunately, in the recent years, Sustainable Development (in its wider sense, from environmental, to economic and social perspective) has acquired a relevant part of the scene and many actions (regulations, legislations, standards, normative, etc.) are pushing sustainability in our society.

In such a context, the design of modern products might more and more take into account these sustainable issues for creating eco-friendly and socially acceptable solutions. Product design might at the same time considers the new “dimensions” assumed by a product, that moved, in the last years, from being a mere artifact to a complex element of tangible and intangible assets. Today a product is a unique selling proposition, in which the physical artifact is extended by a surrounding provision of services, defining the concept of Product-Service System (PSS) [54]. It is a matter of fact that in many industrial sectors companies are generating a relevant part of their business revenues by selling product-related services, like maintenance or repair; some companies (e.g. the well-known Rolls-Royce airplane engine-maker company [75]) have totally shifted their business model by no more “selling engines”, but “flying hours” to their customers.

In this situation, sustainability assumes a systemic perspective and it becomes a matter of optimization in the use of available resources along the entire life cycle of a product (e.g. a car, an airplane engine, a production machine, etc.). This optimization could be achieved with the collaboration of all the actors involved in the life cycle (i.e. designers, manufacturers, suppliers, customers, service providers, recyclers, etc.), who can (or cannot) adopt sustainable practices. Obviously, designers and engineers, being responsible of the system design since its early life cycle stages, have a relevant role in sustainability decisions. It is up to them to find solutions for creating less polluting cars, for studying more reliable engines, for using energy efficient production processes, and also for implementing solutions for supporting new services enabling more sustainable customers’ behaviors. Designers and engineers can assume sustainable decisions using their knowledge, which is obtained following the typical process of knowledge capture, accumulation, and reuse. Knowledge is generated with a scientific method: designers formulate the solution (one or more), test it, analyse the results, and then keep the decision. Unfortunately, designers are often not aware of the all phases that the product they are creating will meet in its life. Moreover, they have to manage a large amount of data and information, often without having adequate tools for considering the implications of their choices in terms of sustainable impacts.

Therefore, a general optimization for reaching a more sustainable condition can be obtained only by accumulating and managing efficiency a deep knowledge on the entire system life cycle (i.e. collecting information about the product realization, utilization, maintenance and disposal) and providing it to designers and engineers in the easiest possible way, with advanced techniques and tools. This should be done also considering the entire service network linked to the product, to guarantee the correct use of all the information related to services.

Since may years, designers and engineers have been supported in their activities by a plethora (e.g. [48]) of computer-aided (CAx) tools, for modeling components and items, test and simulate their behaviors in a virtual environment, and store the obtained results, accumulating knowledge, in common spaces and data warehouses. In the last 30 years, the digitalization of a product has moved from the digital drawing, to digital models, processes and knowledge. As shown in Figure 1, since the ‘70ies many efforts have been spent in transforming paper-based product information into digital formats. Product models and processes started to be digitalized from the second half of the ‘80ies. Nowadays, CAD 3D systems provide excellent visualization functionalities, giving to the designers the possibility to simulate in more and more advanced environments their ideas, in terms of products appearances, dimensions, as well as components interfacing. Furthermore, CAE (Computer Aided Engineering) tools have adopted extensively simulation approaches, supporting designers in their virtual tests and experiments on digitally modeled products. For example, the Finite Element Method and all related applications to material stress, fluid flow and heat transfer, became in the last 15 years very well-known and it was made available in desktop tools for testing and prototyping physical components, by simulating their behaviors under realistic conditions. On the manufacturing engineering side, CAPP (Computer Aided Process Planning) tools have been created for supporting production engineers in the definition and simulation of manufacturing and assembly processes. KBE (Knowledge Based Engineering) environments have been set up for supporting the automation of design procedures and rules, reducing boring and redundant tasks in the daily design work. All these efforts have been characterized by their highly specialization to a specific issue, considering a particular phase of the system life cycle and trying to obtain a good solution for a particular problem in a limited context. Given this picture, a step further must be made by enabling new simulation tools and methods for virtually emulating the product behavior during its expected operating life cycle. This means a new era in the virtual prototyping evolutionary chain, which can be called “Digital Life Cycle” wave. This wave might offer to designers and engineers of the next decade the access to new simulation solutions (Figure 2) that might consider, in parallel, product and service models, through time-dependent architectures, for taking better life cycle-related decisions.

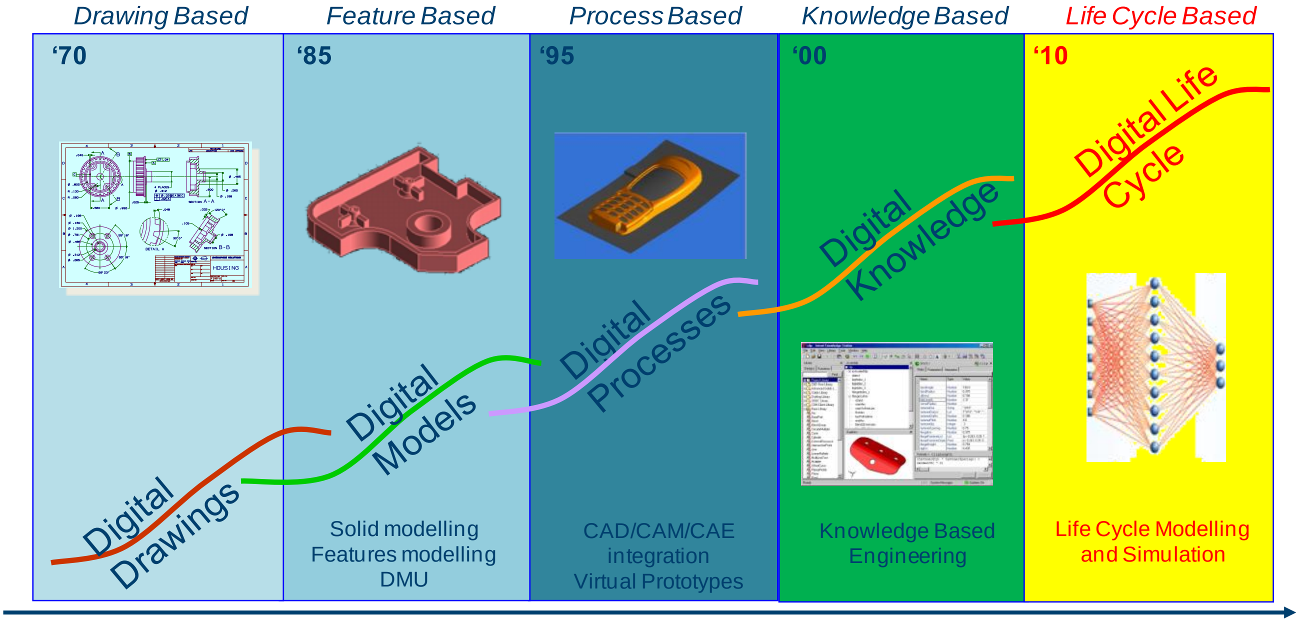


Figure 1. The new wave of virtual prototyping: Digital Life Cycle (images from internet)

The main aim of this paper is to discuss on this evolutionary path, extracting from the current state of the art of the Life Cycle Simulation (LCS) tools, that only partially address the issues of an overall simulation of the product life cycle, useful information for the development of the future LCS tools. . The paper is organized as follow: chapter 2 illustrates the current state of the art in LCS, going into details with a classification of available papers on this topic; chapter 3 discusses a list of relevant issues for the development of a comprehensive LCS tool; chapter 4 describes the proposal of a reference architecture for the design of a future PSS (Product Service System) simulation platform, before the conclusions in chapter 5.

2 State of the Art of Life Cycle Simulation

The management and the analysis of a product life cycle is a well-known concept in literature. Methods and techniques for measuring and assessing the life cycle dimension of a product were created years ago (e.g. [27] for Life Cycle Assessment (LCA)/Life Cycle Engineering (LCE), [37] for Life Cycle Costs (LCC)). These well-known methodologies are the basis of the life cycle design approach. In general terms, they are used for conducting a deep analysis of the different stages of the product life cycle, accumulating product knowledge and defining different scenarios related with a particular product life cycle.

Simulation has acquired an important role along the life cycle design phase because it provides tools for evaluating the performances of a system in virtual environments. Business and design process simulations have been extensively studied in the past and lots of techniques, approaches and tools exist. For example, in some research works (e.g. [17], [35], [47]) Discrete Event Simulation is used to evaluate a product life cycle by summarizing total amount of wastes, energy usage, and revenue and profits a company achieves throughout a certain time period. In other works, (e.g. [10]), System Dynamics is preferred for analysing different PSS propositions under different market conditions.

In such a context, it is interesting to study, from one hand, the current matches between traditional methods (LCC, LCE, and LCA) and simulation techniques and, from the other, what are the existing gaps. In literature, there are many references directly related to product life cycle design and simulation, as shown in Table 1. This table classifies 43 contributions of the last 15 years into 3 clusters according to their main content: (i) Conceptual contribution, (ii) Technological development, and (iii) Industrial applications.

Author	*Conceptual contribution*	*Technological development*	*Industrial applications*
[1] Aiyoshi and Maki			X
[4] Aoyama and Nomoto			X
[8] Asiedu and Gu	X		
[10] Bianchi et al.		X	
[14] Cameron and Ingram			X
[15] Finne	X		
[16] Fleischer et al.			X
[17] Fujimoto et al.	X		
[18] Gabel et al.			X
[20] Gonçalves and Siqueira		X	
[26] Hayek et al.			X
[30] Kimura and Hata		X	
[31] Kiritsis et al.		X	
[32] Kobayashi and Kumazawa	X		
[33] Komerath and Maughmer			X
[34] Komoto et al.		X	
[35] Komoto et al.	X		
[36] Komoto et al.		X	
[37] Korpi and Risku			X
[38] Kubota et al.	X		
[40] Li and Liu	X		
[41] Lipman and Delucchi			X
[44] Meier and Massberg	X		
[45] Meier et al.	X		
[46] Nakano et al.	X		
[47] Nonomura et al.		X	
[48] Noor		X	
[49] Oscarsson and Moris	X		
[51] Sakai et al.	X		
[56] Sakita and Mori	X		
[57] Sakita and Mori	X		
[58] Sandberg et al.			X
[65] Shu et al.	X		
[69] Takata et al.	X		
[70] Takata et al.	X		
[71] Takata et al.			X
[73] Wang et al.		X	
[75] Wong et al.			X
[76] Xiao et al.		X	
[77] Xiao et al.		X	
[78] Xie and Simon		X	
[79] Yamada and Takata			X
[82] Yu and Tao			X

Table 1. Classification of life cycle simulation literature

The “Conceptual contribution” column considers papers mainly dealing with an explanation of the life cycle simulation concept, making state of the art analyses and describing new LCS methods to be adopted. From this point of view, it seems that the LCS concept is well structured and there are lots of available state of the art analyses and methods. However, there are, again, many gaps to fill among the experts. For example, there are several discordances in the definition of life cycle boundaries, in how much the model should be complex, in what should be the simulation inputs and outputs.

The “Technological development” column includes contributions that, mainly, describe the development of the code of simulation software tools without a practical industrial implementation. In general, Discrete Event Simulation (e.g. [20]) and System Dynamics (e.g. [10]) are the most common simulation methods and are used in a wide range of situations. From the software characteristics point of view, general-purpose software tools are mainly used, for example developed in XML and JAVA (e.g. [20]). These tools have the advantage of being very flexible, but on the other hand, they require more work to represent correctly the problem. Another alternative is the use of specific software tools, for example developed in Python (e.g. [36]), also having the capability to be customized according to the problem and dataset at hand. The lack in standard simulation software languages seems to be the main problem for the technological point of view.

Finally, under the "Industrial applications" column, there are papers mainly describing real implementations, experiments and results derived from the use of life cycle simulation tools within industrial companies. In accordance with the survey of Cameron and Ingram [14] on process modeling across the life cycle, the most common reason for modeling, in 95% of cases, are providing insights for product/process design and for optimizing operations. Some 80%, also, replied that modeling is driven by the need for financial and feasibility assessment. Generally, in these research works LCC, LCE and LCA methodologies are applied together, supported by a simulation tool for testing and estimating different application scenarios. Industrial application examples of life cycle simulation refer to:

- Facility management: Takata et al. [69, 70, 71] have developed an information infrastructure for life cycle management, which provides an environment for information sharing throughout the facility life cycle, and computer tools, which support analysis and evaluation required for facility management.
- Industrial robot manufacturing: Yamada and Takata [79] describe a new life cycle simulation method for this aim.
- Welded joint ship structures: Aoyama and Nomoto [4] use life cycle simulation to consider the effect of corrosion of the welded joint of a ship structure and for evaluating product deterioration by corrosion of the welded joint.
- Airborne emissions of biomass-based ethanol products: Yu and Tao [82] describe some interesting applications of life cycle assessment and simulation.
- Cement manufacturing: Gäbel et al. [18] use simulation for the evaluation of environmental performances, product performances and costs.
- Electric and electronic products manufacturing: Fujimoto et al. [17] use life cycle simulation and LCA analysis to compare their performances on a real base.
- Aerospace Engineering: Komerath and Maughmer [33] describe the use of life cycle simulation for the education of aerospace engineers.
- Elevators maintenance design: Kimura and Hata [30] speak about the application of life cycle simulation for the evaluation of maintenance performances on different life cycle scenarios.

The literature analysis conducted underlines that the concept of computer aided solutions able to implement a simulation of different product life cycle phases is a common idea, with several available techniques and industrial experiences demonstrating its usefulness. Simulation is used for:

- Combining flexibility and costs of production (e.g. [46]).
- Estimating financial and environmental revenues (e.g. [32]).
- Reaching ecological potentials while fulfilling economic constraints, given the dependency on specific products (e.g. [44], [51]).
- Getting an overview of the social / environmental influences of the designed product (e.g. [56], [57]).
- Predicting the effect on future costs or risks of modifying designs (e.g. [78]).
- Assisting waste management using the output graphs of disposed components or products (e.g. [78]).
- Modelling economics of component remanufacturing or reuse (e.g. [65], [78]).
- Reducing environmental impacts while extending business opportunities during the development of Service-Oriented Products (e.g. [17]).
- Creating a collaborative/integrated environment for virtual product and process development and for technological/geometrical modelling (e.g. [48]).
- Evaluating product-service quality variations and conceptual life cycle design options (e.g. [30]).

Summarizing, simulation is generally used for the evaluation of two main issues: (i) product life cycle related costs and (ii) product life cycle related environmental impacts. In both these categories, a wide range of simulation tools were developed, from spreadsheets, mathematical software and programming languages to specialist computational packages.

2.1 Simulation and service design

The first simulation tools for the product life cycle appeared in the second half of the '90ies for cost estimation activities. Considering that over 70% of the total life cycle cost of a product is generally committed at the early design stage (e.g. [8]), it is easy to understand why simulation has been primary applied to estimate product costs. However, cost estimation depends on the integrated solution of the complete set of design problems in the early concept of the design phase (e.g. [8], [75]). Given the great span and complexity of the overall problem, the exclusive use of optimization methods is not possible. In fact, the calculation of life cycle cost involves a highly diverse set of representations and processes that makes undesirable to use a single software tool to undertake this task (e.g. [75]). In fact, the tool must be able to model many different situations and use different data types and models to perform the necessary calculations. One possibility (e.g. [41]) is to use general-purpose or specific simulation software tools, but this choice introduces a trade-off between flexibility and optimization. At the beginning of 2K, many authors (e.g. [17], [31], [32], [35], [41], [44], [49], [51], [70], [71], [78]) raised also the awareness towards environmental issues. To this concern, many research started to study the use of simulation for assisting designers in forecasting possible future strategies, environmental impacts and costs associated with alternative design and development decisions. Among them, Takata et al. [70] defines a procedure to organize a system of environmental indicators to be simulated; Fujimoto et al. [17], instead, speaks about life cycle simulation for Service-Oriented Products development. From 2005, the number of authors (e.g. [15], [20] [34], [46], [56], [58], [73], [75], [76], [77]) that expressed the need and proposed new paradigms in life cycle modeling and simulation has grown, enabling the virtualization of every stage of the product life cycle, from its design, to its use and dismission. Valuable research works have been poblisshed to this concern (e.g. [10], [15], [26], [31], [34], [35], [36], [40], [45], [47], [58], [73], [75], [76], [77]). These authors started to include in their simulation models also the role of product-related services, trying to simulate / estimate the fact that a product is not just an artifact, but it is a complex solution, coming from the sum of the real product plus the related services (generally defined in literature as PSS - Product Service Solutions, e.g. [54]).

Therefore, in parallel with the advent of life cycle simulation, authors started to include in their simulation approaches also the role of product-related services. For this aim, the concepts of Service/Product Engineering and Service CAD system were defined. The first one, it's a discipline that considers the service (not the product) as the key factor of the customer's value (e.g. [9], [13], [21], [22], [23], [24], [25], [28], [29], [42], [43], [67], [68], [72], [81]). The second one, instead, it's a new technique for the creation of computerized tools supporting service design activities (e.g. [5], [6], [7], [11], [52], [53], [54], [55], [60], [61], [62], [63], [64]). From the Service CAD and the Service/Product Engineering points of view, there many industrial applications can be found. Komoto and Tomiyama [35] propose an Integrated Service and Life Cycle simulator (ISLC) that aids designers to define and search PSSs as a combination of service contents, service channels and corresponding activities, defined in the so-called "Service CAD". From the Service Design point of view, or the translation of ideas about a new services in drawings and specifications (e.g. [19]), there are lots of papers speaking about Service-Oriented Architecture (SOA) models and applications (e.g. [31]), Service-Oriented Simulation (e.g. [38], [73]), Service-Oriented Computing (e.g. [50]) supporting designers during the service concept and development phases and modeling frameworks for complex product virtual prototyping management (e.g. [76], [77]). However, more recent papers (e.g. [66]) underline that "there is no empirical validation of successful software architecture principles for service design". Sangiorgi [59] adds that, "when both the complexity of challenges and the objects of design become larger, design needs to collaborate with a wider number of stakeholders and professions, but also to work 'within' service organisations and users communities to provide tools and models to deal with change and complexity on a daily basis". Because the results of design depend more on what designers perceive design is, than from a stable definition elaborated by a scientific community, new simulation tools are needed, driving service designers in selecting the best decision both from the service and the product view. In particular when "dealing with complex challenges of sustainable development, the designer can become a connector between multiple stakeholders, teasing out issues and finding common values". However, starting from the common idea that service adds value to the product, it can be concluded, as reported by lots of authors (e.g. [2], [3], [72], [78]), that a better platform connecting Service Engineering methods and LCS tools is needed.

3 Discussion

After having explored the literature reagrding LCS, it is possible to confirm that a standardized way for LCS doesn't already exists. There are, instead, lots of simulation techniques useful for a particular sector or purpose. The need for a better way of doing simulation during the early design phase and considering the whole life cycle can be therefore concidered a well-known issue among the experts. What could be scientifically interesting and, at the same time, useful for the future industrial applications of the LCS concept is a classification of the main characteristics to consider for the development of new advanced life cycle simulation platforms. From the previous analysis, 4 dimensions have been defined as relevant topics to be considered in LCS: (i) modularity, (ii) life cycle cost perspective, (iii) stochastic behavior of modules, and (iv) social and environmental impacts.

3.1 Modularity

Modularization of different parts composing the potential LCS platform is a must. This characteristic, enhanced by many authors, is useful to create a virtual environment able to be as flexible as possible for an extended use in various scenarios and applications. This is one of the main problems evidenced by the experts. Sound examples are those of Nonomura et al. [47], and subsequently Fujimoto et al. [17], in which a life cycle simulation approach for configuring modular products is presented. The model, in these cases, is a composition of three sub-models (a life cycle process model, a product model, and a user model). The first one represents a product life cycle as a network of processes, such as manufacturing, operation, recycling, and remanufacturing. The product is modeled as a set of modules and each of them is modeled by a set of attributive parameters. The user model is implied to fix the customer behaviors in the market. LCS simulates flows of products, materials, money, and information based on a given life cycle model using a discrete event simulation technique, such as Petri Nets, and evaluates a product life cycle by summarizing the total amount of wastes, energy usage, revenues and profits a company achieves throughout a certain time period. Another type of modularization, a little bit different, is described in Komoto et al. [35]. In this case, the simulation model is implied for the description of systematic forms of PSSs and for the environmental and economic evaluation of alternative PSS solutions. The life cycle model for LCS used in this study consists of a product model and a process network. In addition, performance indicators are defined for the evaluation of the simulation results. The life cycle simulation model is a service CAD integrated with a life cycle simulator through an object-oriented, process-based discrete event simulation language.

3.2 Life cycle cost perspective

LCC evaluation is the primary application of LCS methods. Nowadays, even if with a different point of view, LCC is important not only for an economical point of view, but also for social and environmental implications. Relevant examples come from the aero-engine sector. Wong et al. [75] is one of the most common papers mentioned in literature for the "Design for Service" paradigm. It describe the program implemented by Rolls-Royce, which advocates designing products and services in parallel, considering life cycle performances and developing design tools to predict the total life cycle cost. This approach links two different commercial software packages, a top level hierarchical tool able to model unit cost and physics based life predictions and a discrete event simulation tool which models dynamic processes or systems. The top level hierarchical model collates all the necessary input data and passes it on to a relational database. The top level hierarchical model is also integrated with the above mentioned models to predict component unit costs and component deterioration lives. The discrete event simulation model subsequently retrieves this data from the database to calculate maintenance costs. The simulation results are then passed back to the database. Finally, the simulation data is post-processed by the hierarchical tool as it has superior statistical analysis functions. From the same sector, Sandberg et al. [58] describe a model for cost prediction that introduce evaluation of post-manufacturing activities in the early concept designs phase for hardware parts of functional products (including both hardware and service). A model has been proposed to handle the information flow between teams when developing structural jet engine components. Aspects concerning design, manufacturing, performance, and maintenance of jet engine flanges were included in the model by means of a Knowledge Based Engineering (KBE) system coupled to databases and spreadsheets. In this research, a parametric cost estimation technique is utilized with a KBE tool to couple the geometry definition process to the cost estimation activity.

3.3 Stochastic behavior of modules

A predefined statistical behavior of the modules composing the LCS platform is another common way of thinking in literature. The example reported in Hayek et al. [26] presents a simulation model allowing maintenance and replacement decisions. The methodology is based on simulating the up-time of the machine or process as a series of critical modules. Each module is characterized by an empirically derived failure distribution. When data of specific modules are imported into the simulation platform from the database, a Weibull distribution with the imported parameters is assigned to each module. Then, the software draws a random number from each distribution, and assigns it to its corresponding module's failure time. Repeating these steps a large number of times will lead to a probability distribution that describes the removal times of the product. As the product is removed, it enters the shop for service. In the shop, the product is dismantled, and the user can simulate a number of key alternatives and scenarios. Another way of thinking is reported in Kimura and Hata [30]. They describe an approach to model product life cycle behavior by using state transition modeling. In this case, product behavior and performance are modeled by stochastic or statistical transition among associated states which correspond to different status of products or parts. State transition information is derived from existing product data, or can be computed by a method based on functional modelling and computer aided Failure Mode and Effect Analysis.

3.4 Social and environmental impacts

The assessment of social and environmental impacts thorough LCS is, in general terms, a characteristics founded in a lot of works. However, it is especially enhanced into three papers (e.g. [17], [56], [57]). Sakita and Mori [56, 57] underline the link between social and environmental aspects during the development phase. They propose a multi-leveled product life cycle simulation system for product development based on the interaction of subjects. The subjects are dynamically changed by flow of physical and social entities. Then, the subjects grow or decline. The influences of designing product are simulated and estimated by changes of subjects and flow of physical and social entities. Fujimoto et al. [17], instead, uses a series of environmental indexes for the performance evaluation of their LCS model in terms of total wastes, energy consumption, revenues and profits improvements.

Summarizing all these apports from the literature it is important to highlight that, especially within the Japanese research works, the studied situations are related to high volume products, for which the issues addressed are mainly at the strategic level. In fact, products are generally modeled as product families and their behavior is statistically defined. In the same way, the service solution is also statistically modeled. The resulting implementation leads to a very abstract and time independent model that does not answer to the needs of companies producing special products, which need to be individually addressed in their life cycle behavior and service needs. Thus, a different approach is necessary in these cases, being able to model individual products that may be customized to their particular service needs and individual degradation scenarios. Such an approach must be necessarily based on modular components so to solve the problem with a standard software solution which may be customized to any specific application case.

4 Proposal of a reference architecture for Life Cycle Simulation

What can be evidenced, considering the previous literature analysis and discussion about LCS practices, is that, nowadays, a simulation software tool or platform that respects all the guidelines stated above is not yet available. All of the available solutions are, in general, specifically designed taking into account only some of these characteristics. Hence, a different type of architecture is needed for the future design of product service systems.

Technically, the creation of a reference architecture will be possible by integrating specific modules and already existing simulation tools to create a comprehensive solution for analysing the entire life cycle of a PSS. The vision is to develop a simulation toolbox, in which the different components describing the product behavior and the service operations can be put together easily and accordingly customized to a specific application case. Using this tool, a company may evaluate what kind of services are necessary for its products and/or what kind of modifications should be made to its products and/or to the network of its service system to gain market share. The simulation tool should be composed by three main parts:

- A Product Simulator Module, in which both physical laws and statistical product behavior are used to virtually emulate the behavior of a physical product during its life cycle. Such a model could be instantiated selecting components from a series of libraries (derived by different product data repositories), building a unique virtual product instance to be simulated for each product (Product Model). Such a virtual model will simulate the evolution of the life status of the product, generating individual service requests (e.g. a maintenance service request to be provided after a fault).

- A Services Simulator Module, in which different service solutions related to the product-service needs are modeled. Such a library could be built upon an ontology of product-services by putting together models of individual services made of discrete resources involving both deterministic and statistical behavior. Using these components, the user may build a service solution thus creating a specific service network (Services Model) supporting the services needed by a given set of products. The Services Model could be used for evaluating different scenarios of interaction among the services needs of products and their support by the service network in terms of relevant performances (e.g. service level, cost, environmental impact, etc.).

- Finally, the third part of the tool is made by an Integration Platform (Figure 2) in which all previous components are integrated. After integration, the various instances of a product model can interact with a given instance of the services model, thus allowing the generation of a PSS model instance to be emulated and experimented in a virtual environment. The emulation of the PSS model instance will be allowed by a simulation engine also working within the Integration Platform.

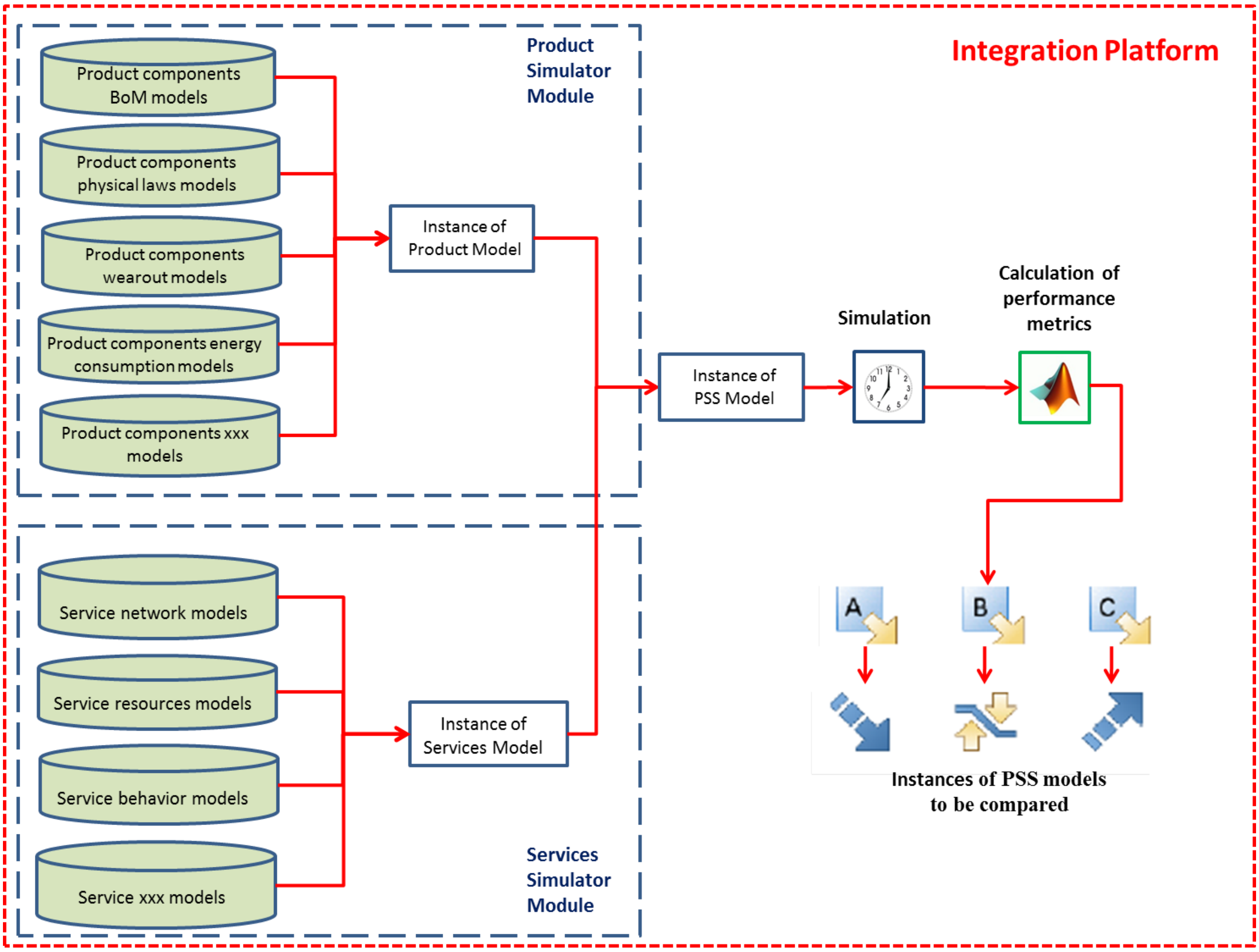


Figure 2. Schematic view of the Integration Platform

The aim of this reference architecture is to create a new approach to product-service life cycle simulation in which each product can be modeled as an individual entity (and not as a family, or product type, as simplified in the works available in literature) that evolve independently in time and express service requests during its life cycle. The service network, instead, assumes the use of physical modeling and is made up of components (modular solutions) that, joined together, create the needed service model. The service network will be a discrete model composed by entities (products, materials, resources) and events (e.g. service requests like maintenance activities, product upgrade services, etc.). This way, a dynamic and realistic view of the service network activity will be developed and it will be possible to use standard simulation tools for emulating the service network.

The development of a new simulation environment for testing and prototyping PSS could be a good way to face with modern sustainability issues. Such a kind of environment should permit the definition of the different services (e.g. maintenance, reconfiguration, upgrade, recycling, dismissal, etc.) to be provided during the life cycle of a product, also in terms of business processes to be activated, measured and revised. The use of simulation for the virtual emulation of a service network could offer a good support to engineers and designers of the modern companies to develop a comprehensive PSS and not just to design a mere artifact.

5 Conclusions

The present paper had the aim to present, thorough a detailed state of the art analysis, current trends, characteristics and industrial applications of Life Cycle Simulation for PSS design. Strengthens to consider and weaknesses to avoid in the development of future simulation tools have been discussed. From the analysis some important guidelines were extracted to support the industrial and scientific development of the next generation of life cycle-oriented simulation tools. The guidelines are summarized in four points: (i) modularity, (ii) LCC perspective, (iii) statistical/stochastic behavior of modules and (iv) social/environmental impact. Starting from these points, in the last chapter a reference architecture is proposed for Product-Service Systems Design. However, even if it considers all the previous guidelines, the reference architecture proposed in this work is only a conceptual model, without a practical implementation. Anyway, this model could be the first step towards the development of a future simulation tool.

References

1. Aiyoshi, E., Maki, A.: Life cycle simulation based on the feedback system and the choice of switching time for the period model. J. Math. Comput. Simul. 39, 335--341 (1995)
2. Alix, T., Vallespir, B.: Product and complementary service: looking for the right pair. In: Proceedings of the Service Systems and Service Management International Conference, pp. 720--725. IEEE Press (2006)
3. Alix, T., Ducq, Y., Vallespir, B.: Product service value analysis: two complementary points of view. In: Proceedings of the 1st CIRP Industrial Product-Service Systems (IPS2) Conference, pp. 157, Cranfield University (2009)
4. Aoyama, K., Nomoto, T.: Life-Cycle Simulation Model for Large Scale Welded Structure - A Basic Study on Welded Joint Model with Consideration of the Welded Joint Corrosion. In: EcoDesign ‘99, 1st International Symposium on Environmentally Conscious Design and Inverse Manufacturing, pp. 790--795. IEEE Press, Tokyo (1999)
5. Arai, T., Shimomura, Y.: Proposal of Service CAD System - A Tool for Service Engineering. CIRP Annals - Manuf. Tech. (2004)
6. Arai, T., Shimomura, Y.: Service CAD System - Evaluation and Quantification. CIRP Annals - Manuf. Tech. (2005)
7. Arai, T., Hara, T., Shimomura, Y., Yoshimitsu, Y.: Service Engineering: a CAD system of service to evaluate satisfaction of products. In: The 9th IEEE International Conference on E-Commerce Technology and the 4th IEEE International Conference on Enterprise Computing, E-Commerce and E-Services (CEC-EEE), (2007)
8. Asiedu, Y., Gu, P.: Product life cycle cost analysis: state of the art review. Int. J. Prod. Res. 36/4, 883--908 (1998)
9. Aurich, J.C., Fuchs, C., Wagenknecht, C.: Life cycle oriented design of technical Product-Service Systems. J. Clean. Prod., vol. 14, pp. 1480--1494 (2006)
10. Bianchi, N.P., Evans, S., Revetria, R., Tonelli, F.: Influencing Factors of Successful Transitions towards Product-Service Systems: a Simulation Approach. Int. J. Math. Comput. Simul. Issue 1, vol. 3, pp. 30--43 (2009)
11. Boyonas, M.I., Hara, T., Arai, T., Shimomura, Y.: Service Analysis for Service Design Process Formalization based on Service Engineering. In: Proceedings of the 14th CIRP Conference on Life Cycle Engineering, 11--13 June, Tokyo (2007)
12. Brundtland Commission, Our Common Future, Report of the World Commission on Environment and Development, World Commission on Environment and Development, Published as Annex to General Assembly document A/42/427, Development and International Co-operation: Environment, August 2 (1987)
13. Bullinger, H-J., Fahnrich, K-P., Meiren, T.: Service engineering—methodical development of new service products. Int. J. Prod. Econ., vol 85, pp. 275--287 (2003)
14. Cameron, I.T., Ingram, G.D.: A survey of industrial process modelling across the product and process life cycle. J. Comput. Chem. Eng. 32, 420--438 (2008)
15. Finne, M.: The design of industrial service offerings in indirect channels. Master of Science Thesis in Industrial Engineering and Management, Helsinki University of Technology. Espoo (2009)
16. Fleischer, J., Broos, A., Schopp, M., Wieser, J., Hennrich, H.: Life cycle-oriented component selection for machine tools based on multibody simulation and component life prediction. CIRP J. Manuf. Sci. Tech. 1, 179--184 (2009)
17. Fujimoto J., Umeda Y., Tamura T., Tomiyama T., Kimura F.: Development of Service-Oriented Products Based on the Inverse Manufacturing Concept. J. Environ. Sci. Tech. 37/23, pp. 5398--5406 (2003)
18. Gäbel, K., Forsberg, P., Tillman, A-M.: The design and building of a life cycle based process model for simulating environmental performance, product performance and cost in cement manufacturing. J. Clean. Prod. 12, 77--93 (2004)
19. Goldstein, S.M., Johnston, R., Duffy, J., Rao, J.: The service concept: the missing link in service design research. J. Oper. Manuf., vol. 20, pp. 121--134 (2002)
20. Gonçalves Cople, D., Siqueira Brick, E.: A simulation framework for technical systems life cycle cost analysis. J. Simul. Modell. Prac. Theor. 18, 9--34 (2010)
21. Hara, T., Arai, T., Shimomura, Y.: A Concept of Service Engineering: A Modeling Method and A Tool for Service Design. In: Proceedings of the International conference on Service Systems and Service Management pp. 13--18, Troyes (2006), DOI 10.1109/ICSSSM.2006.320581
22. Hara, T., Arai, T., Shimomura, Y., Sakao, T.: Service/Product Engineering: a new discipline for value production. In: Proceedings of the 19th Conference on Production Research (2008)
23. Hara, T., Arai, T., Shimomura, Y.: A Method to Analyze PSS from the Viewpoints of Function, Service Activity and Product Behavior. In: Proceedings of the 1st CIRP Industrial Product-Service Systems (IPS2) Conference, Cranfield, pp. 180 (2009)
24. Harada, K., Arai, T., Hara, T., Shimomura, Y.: Definition of Design Operation for Service. In: The 41st CIRP Conference on Manufacturing Systems, pp. 481--484 (2008)
25. Huang, J.Q., Qu, T., Zhong, R.Y., Li, Z., Yang, H.D., Zhang, Y.F., Chen, Q.X., Jiang, P.Y., Chen, X.: Establishing production service system and information collaboration platform for mold and die products. Int. J. Adv. Manuf. Tech., vol. 52, pp. 1149--1160 (2011)
26. Hayek, M.E., van Voorthuysen, E., Kelly, D.W.: Optimizing life cycle cost of complex machinery with rotable modules using simulation. J. Qual. Maint. Eng. 11/4, 333--347 (2005)
27. Jensen, A.A., Elkington, J., Christiansen, K., Hoffmann, L., Moller, B. T., Schmidt, A. and van Dijk, F.: Life Cycle Assessment: A guide to approaches, experiences and information sources. Report to European Environment Agency, Copenhagen (1997), http://www.eea.eu.int/
28. Kimita, K., Hara, T., Shimomura, Y., Arai, T.: Cost Evaluation Method for Service Design Based on Activity Based Costing. In: The 41st CIRP Conference on Manufacturing Systems, pp. 477--480 (2008)
29. Kimita, K., Hara, T., Shimomura, Y., Arai, T.: Evaluation of customer satisfaction for PSS design. J. Manuf. Tech. Manag., vol 20, n° 5, pp. 654--673 (2009)
30. Kimura, F., Hata, T.: Life Cycle Design and Management based on Simulation of Service Quality Variation. In: CIRP seminar on life cycle engineering, Copenhagen, Denmark (2003)

31. Kiritsis, D., Bufardi, A., Xirouchakis, P.: Research issues on product life cycle management and information tracking using smart embedded systems. J. Adv. Eng. Inf. 17, 189--202 (2003)
32. Kobayashi, H., Kumazawa, T.: A Simulation-based Decision Support Methodology for Reuse Business. In: EcoDesign2005/3A-1-2F, 4th International Symposium on Environmentally Conscious Design and Inverse Manufacturing, pp. 598--605. IEEE Press, Tokyo (2005)
33. Komerath, N., Maughmer, M.D.: Educating the Aerospace Engineer of 2016. In: ASEE 2005, American Society of Engineering Education Annual Conference & Exposition (2005)
34. Komoto, H., Tomiyama, T., Nagel, M., Silvester, S., Brezet, H.: Life Cycle Simulation for Analyzing Product Service Systems. In: EcoDesign2005/2B-1-2F, 4th International Symposium on Environmentally Conscious Design and Inverse Manufacturing, pp. 386--393. IEEE Press, Tokyo (2005)
35. Komoto, H., Tomiyama, T.: Integration of a service CAD and a life cycle simulator. CIRP Annals - Manuf. Tech. 57, 9--12 (2008)
36. Komoto, H., Tomiyama, T., Silvester, S., Brezet, H.: Analyzing supply chain robustness for OEMs from a life cycle perspective using life cycle simulation. Int. J. Prod. Econ., doi:10.1016/j.ijpe.2009.11.017, Elsevier (2009)
37. Korpi, E., Risku, T.A.: Life cycle costing: a review of published case studies. J. Manuf. Aud. 23/3, 240--261 (2008)
38. Kubota, F., Sato, S., Nakano, M.: Enterprise Modeling and Simulation Platform Integrating Manufacturing System Design and Supply Chain. In: Proceedings of SMC99, IEEE International Conference on Systems, Manufacturing and Cybernetics pp. 511--515. IEEE Press, Tokyo (1999)
39. Li, B.H., Chai, X., Di, Y., Yu, H., Du, Z., Peng, X.: Research on Service Oriented Simulation Grid. In: Proceedings of ISADS05, International Conference of Autonomous Decentralized Systems, pp. 7--14. IEEE Press (2005)
40. Li, X., Liu, Z.G.: An Evolution Framework of Product Service System for Firms across Service Supply Chain with Integrated Life cycle Perspective. In: Proceedings of the international conference on Logistics systems and Intelligent Management pp. 430--434, 9--10 January, Harbin, (2010)
41. Lipman, T.E., Delucchi, M.A.: A retail and life cycle cost analysis of hybrid electric vehicles. J. Trans. Res. Part D 11, 115--132 (2006)
42. Mandelbaum, A.: Service engineering: modeling, analysis and inference of stochastic service networks. Mini course, Faculty of Industrial Engineering and Management Technology, Haifa, Israel, pp. 1--10 (1999)
43. Maussang, N., Zwolinski, P., Brissaud, D.: Evaluation of Product-Service Systems During Early Design Phase. In: Proceedings of the 41st CIRP Conference on Manufacturing Systems, pp. 547--552 (2008)
44. Meier, H., Massberg, W.: Life Cycle-Based Service Design for Innovative Business Models. CIRP Annals - Manuf. Tech. 53/1, 393--396 (2004)
45. Meier, H., Roy, R., Seliger, G.: Industrial Product-Service Systems-IPS^2. CIRP Annals - Manuf. Tech. 59, 607--627 (2010)
46. Nakano, M., Noritake, S., Ohashi, T.: A Life cycle Simulation Framework for Production Systems. In: IFIP International Federation for Information Processing, Tomasz Koch, ed., Lean Business Systems and Beyond. LNCS, vol. 257, pp. 327--335. Springer, Boston (2008)
47. Nonomura, A., Tomiyama, T., Umeda, Y.: Life Cycle Simulation for the Inverse Manufacturing. In: EcoDesign99, 1st International Symposium on Environmentally Conscious Design and Inverse Manufacturing, pp. 712--718. IEEE Press, Tokyo (1999)
48. Noor, A.K.: Emerging CAE Technologies and their role in Future Ambient Intelligence Environments. Cent. Eur. J. Eng. vol. 1, n° 1, pp. 2--8 (2011)
49. Oscarsson, J., Moris, M.U.: Documentation of discrete event simulation models for manufacturing system life cycle simulation. In: 2002 Winter Simulation Conference, E. Yücesan, C.H. Chen, J.L. Snowdon and J.M. Charnes eds. LNCS vol. 2, pp. 1073--1078. IEEE Press (2002)
50. Papazoglu, M.P., Traverso, P., Dustdar, S., Leymann, F.: Service-Oriented Computing: State of the Art and Research Challenges. Pp. 38--45. IEEE Press (2007)
51. Sakai, N., Tanaka, G., Shimomura, Y.: Product Life Cycle Design Based on Product Life Control. In: EcoDesign2003/1D-2, 3rd International Symposium on Environmentally Conscious Design and Inverse Manufacturing, pp. 102--108. IEEE Press, Tokyo (2003)
52. Sakao, T., Shimomura, Y.: Service CAD System to Support Servicification of Manufactures. In: Proceedings of the 14th CIRP Conference on Life Cycle Engineering. Pp. 143--148, 11--13 June, Tokyo (2007)
53. Sakao, T., Shimomura, Y.: Service Engineering: a novel engineering discipline for producers to increase value combining service and product. J. Clean. Prod. 15, pp. 590--604 (2007)
54. Sakao, T., Sandstrom, G.O., Matzen, D.: Framing research for service orientation of manufacturers through PSS approaches. Int. J. Manuf. Tech. Mng, vol. 20, n° 5, pp. 754--778 (2009)
55. Sakao, T., Shimomura, Y., Sundin, E., Comstock, M.: Modeling design objects in CAD system for Service/Product Engineering. J. Comput.-Aided Des. 41, 197--213 (2009)
56. Sakita, K., Mori, T.: Product Life Cycle Simulation System for EcoDesigners. In: Proceedings of Ecodesign 05, 4th International Symposium on Environmentally Conscious Design and Inverse Manufacturing, 2D-2-4S, pp 527--528. IEEE Press (2005)
57. Sakita, K., Mori, T.: Product Life Cycle Simulation System for Environmentally Conscious Product Development. In: LCE2006, 13th CIRP International Conference on Life Cycle Engineering, pp. 239--242. Leuven (2006)
58. Sandberg, M., Boart, P., Larsson, T.: Functional Product Life Cycle Simulation Model for Cost Estimation in Conceptual Design of Jet Engine Components. J. Conc. Eng. 13/4, 331--342 (2005)
59. Sangiorgi, D.: Building up a Framework for Service Design Research. In: Proceedings of EAD09/037, 8th European Academy of Design Conference, pp. 415--420. Aberdeen - Scotland (2009)
60. Shimomura, Y., Tomiyama, T.: Service Modeling for Service Engineering. In: Proceedings of the IFIP 5th International Working Conference of Information Infrastructure System for Manufacturing, vol. 168 pp. 31--38 (2005)
61. Shimomura, Y., Sakao, T., Petti, L., Raggi, A.: Proposal of a Service Design Process Model based on Service Engineering. In: Proceedings of the TMCE, 18--22 April 2006, Ljubljana (2006)
62. Shimomura, Y., Sundin, E., Sakao, T., Lindahl, M.: A Design Process Model and a Computer Tool for Service Design. In: Proceedings of the ASME, International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, 4--7 September 2007, Las Vegas (2007)
63. Shimomura, Y., Sakao, T.: A Service Evaluation Method for Service/Product Engineering. In: Proceedings of the International Conference on Engineering Design (ICED'07), pp. 1--10, 28--31 August, Paris (2007)

64. Shimomura, Y., Hara, T., Arai, T.: A service evaluation method using mathematical methodologies. CIRP Annals - Manuf. Tech. 57, 437--440 (2008)
65. Shu L.H., Wallace D.R., Flowers W.C.: Probabilistic Methods in Life-Cycle Design. In: ISEE-1996, International Symposium on Electronics and the Environment, pp. 7--12. IEEE Press, Tokyo (1996)
66. Stelzer, D.: Enterprise Architecture Principles: Literature Review and Research Directions. ICSOC/ServiceWave 2009, LNCS 6275, pp. 12--21, Springer-Verlag Berlin Heidelberg (2010)
67. Sundin, E., Lindahl, M., Comstock, M., Shimomura, Y., Sakao, T.: Integrated Product and Service Engineering Enabling Mass Customization. In: Proceedings of the 19th Conference on Production Research, (2007)
68. Sundin, E., Östlin, J., Rönnbäck, A.Ö., Lindahl, M., Sandström, G.Ö.: Remanufacturing of Products used in Product Service System Offerings. In: Proceedings of the 41th CIRP Conference on Manufacturing Systems, pp. 537--542 (2008)
69. Takata, S., Yamada, A., Inoue, Y.: Computer-Aided Facility Life Cycle Management. In: EcoDesign ‘99, 1st International Symposium on Environmentally Conscious Design and Inverse Manufacturing, pp. 856--861. IEEE Press, Tokyo (1999)
70. Takata, S., Ogawa, T., Umeda, Y., Inamura, T.: Framework for Systematic Evaluation of Life Cycle Strategy by means of Life Cycle Simulation. In: EcoDesign2003/1B-8, 3rd International Symposium on Environmentally Conscious Design and Inverse Manufacturing, pp. 198--205. IEEE Press, Tokyo (2003)
71. Takata, S., Kimura, F., van Houten, F.J.A.M., Westkämper, E.: Maintenance: Changing Role in Life Cycle Management. CIRP Annals - Manuf. Tech. 53/2, 643--655 (2004)
72. Torney, M., Kuntzky, K., Herrmann, C.: Service Development and Implementation - A Review of the State of the Art. In: Proceedings of the 1st CIRP Industrial Product-Service Systems (IPS2) Conference, pp. 24, Cranfield University (2009)
73. Wang, W-g., Wang, W-p., Zander, J., Zhu, Y-f.: Three-dimensional conceptual model for service-oriented simulation. In: Journal of Zhejiang University SCIENCE A. LNCS vol. 10/8 pp. 1075--1081. Springer (2009)
74. Weigand, H., Johannesson, P., Andersson, B., Bergholtz, M.: Value-Based Service Modeling and Design: Toward a Unified View of Services. In: CAiSE 2009, LNCS 5565, pp. 410--424, Springer-Verlag Berlin Heidelberg (2009)
75. Wong, J.S., Scanlan, J.P., Eres, M.H.: An Integrated Life Cycle Cost Tool for Aero-engines. In: PLM09, International Conference on Product Life cycle Management. Inderscience Enterprises Ltd. (2009)
76. Xiao, S., Li, B.H., Xudong, C.: Research on key technologies of complex product virtual prototype life cycle management (CPVPLM). J. Simulat. Modell. Pract. Theory 16, 387--398 (2008)
77. Xiao, S., Xudong, C., Li, Z., Guanghong, G.: Modeling framework for product life cycle information. J. Simul. Modell. Pract. Theor. (2009)
78. Xie, X., Simon, M.: Simulation for product life cycle management. J. Manuf. Tech. Manag. 17/4, 486--495 (2006)
79. Yamada, A., Takata, S.: Life Cycle Management of Industrial Robots Based on Deterioration Evaluation - Facility Layout and Motion Planning Taking account of Joint Gear Wear. In: EcoDesign2001, 2nd International Symposium on Environmentally Conscious Design and Inverse Manufacturing, pp. 460--465. IEEE Press, Tokyo (2001)
80. Yang, X., Moore, P., Pu, J-S., Wong, C-B.: A practical methodology for realizing product service systems for consumer products. J. Comput. Ind. Eng., vol. 56, pp. 224--235 (2009)
81. Yang, L., Xing, K., Lee, S-H.: Framework for PSS from Service’ Perspective. In: Proceedings of the International Multi-Conference of Engineers and Computer Scientists (IMECS) 2010, Vol. III, March 17-19 Hong Kong (2010)
82. Yu, S., Tao, J.: Simulation based life cycle assessment of airborne emissions of biomass-based ethanol products from different feedstock planting areas in China. J. Clean. Prod. 17, 501--506 (2009)

Table

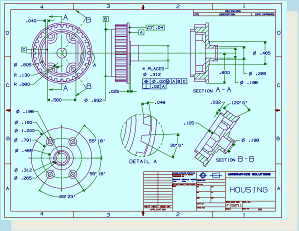
Author	*Conceptual contribution*	*Technological development*	*Industrial applications*
[1] Aiyoshi and Maki			X
[4] Aoyama and Nomoto			X
[8] Asiedu and Gu	X		
[10] Bianchi et al.		X	
[14] Cameron and Ingram			X
[15] Finne	X		
[16] Fleischer et al.			X
[17] Fujimoto et al.	X		
[18] Gabel et al.			X
[20] Gonçalves and Siqueira		X	
[26] Hayek et al.			X
[30] Kimura and Hata		X	
[31] Kiritsis et al.		X	
[32] Kobayashi and Kumazawa	X		
[33] Komerath and Maughmer			X
[34] Komoto et al.		X	
[35] Komoto et al.	X		
[36] Komoto et al.		X	
[37] Korpi and Risku			X
[38] Kubota et al.	X		
[40] Li and Liu	X		
[41] Lipman and Delucchi			X
[44] Meier and Massberg	X		
[45] Meier et al.	X		
[46] Nakano et al.	X		
[47] Nonomura et al.		X	
[48] Noor		X	
[49] Oscarsson and Moris	X		
[51] Sakai et al.	X		
[56] Sakita and Mori	X		
[57] Sakita and Mori	X		
[58] Sandberg et al.			X
[65] Shu et al.	X		
[69] Takata et al.	X		
[70] Takata et al.	X		
[71] Takata et al.			X
[73] Wang et al.		X	
[75] Wong et al.			X
[76] Xiao et al.		X	
[77] Xiao et al.		X	
[78] Xie and Simon		X	
[79] Yamada and Takata			X
[82] Yu and Tao			X

Figure

Lifecycle Simulation

Drawing Based

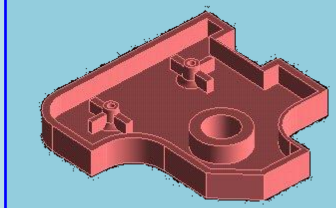
‘70



Digital Drawings

Feature Based

‘85

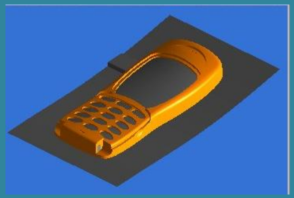


Digital Models

Solid modelling
Features modelling
DMU

Process Based

‘95



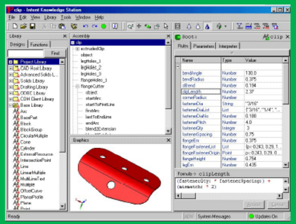
Digital Processes

CAD/CAM/CAE
integration
Virtual Prototypes

Knowledge Based

‘00

Digital Knowledge

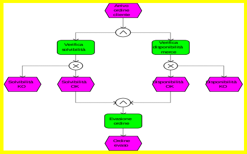


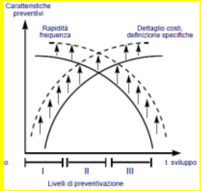
Knowledge Based
Engineering

Lifecycle Based

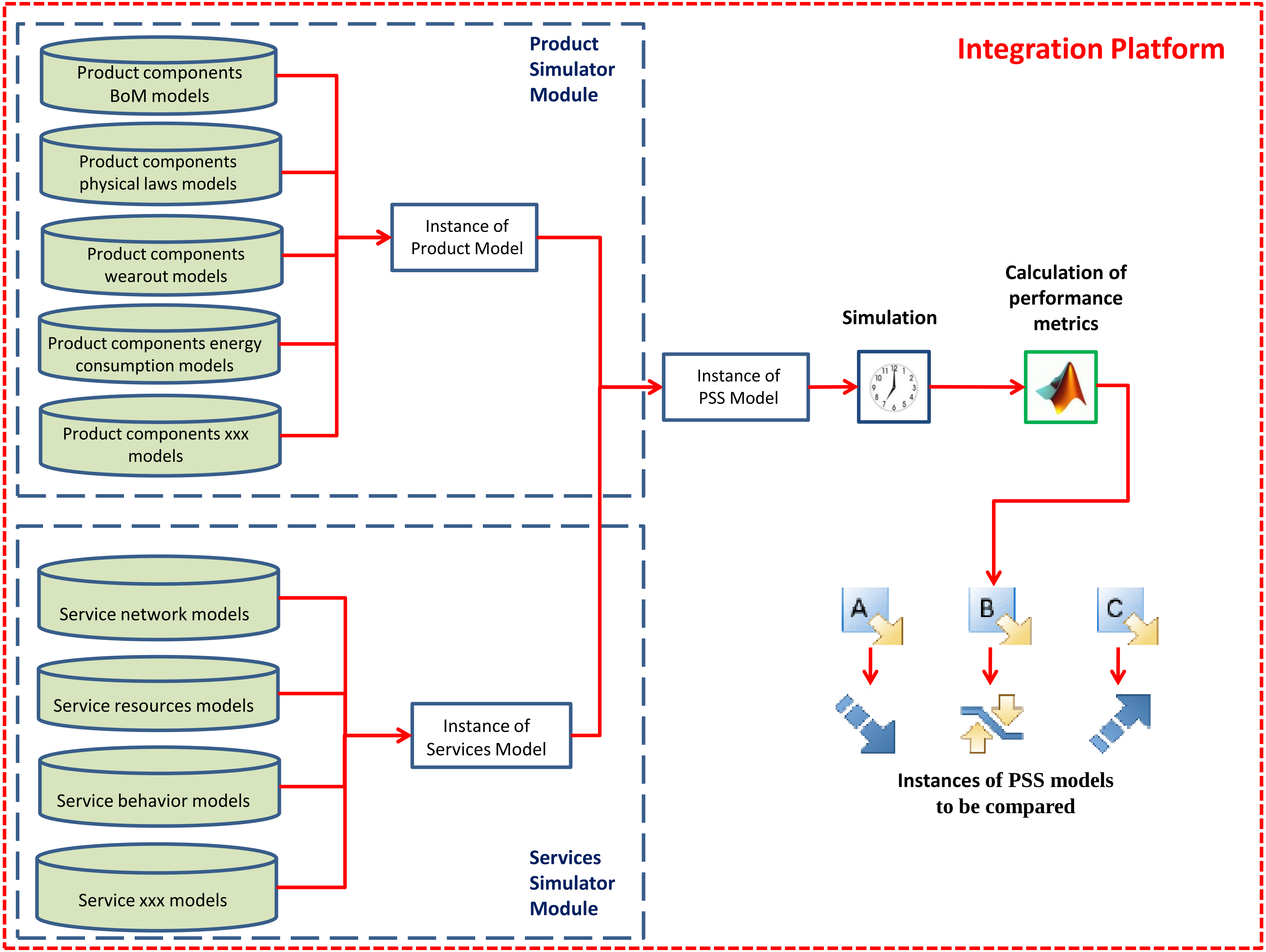
‘10

Digital Lifecycle





Lifecycle Modelling
and Simulation


Integration Platform
Product Simulator Module
Product components BoM models
Product components physical laws models
Product components wearout models
Product components energy consumption models
Product components xxx models
Instance of Product Model
Services Simulator Module
Service network models
Service resources models
Service behavior models
Service xxx models
Instance of Services Model
Instance of PSS Model
Simulation
Calculation of performance metrics
A
B
C
Instances of PSS models to be compared