Research plan: Towards Product-Service Life Cycle Simulation

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Abstract. The present paper discusses the current state of the art about life cycle simulation. The perspective of life cycle is more and more relevant in the current society, which calls for a more sustainable approach to design, engineering and production of every-day things and products. To answer to such a need, designers, planners and engineers might have access to new techniques, methods and tools which are able to integrate in a proper way the life cycle perspective. In such a contest, simulation – in its wider meaning – could play a relevant role. This paper conducts a state of the art of existing approaches and solutions able to support life cycle simulation, in order to identify the main trends and prioritize the next steps.

Keywords: Life cycle simulation, Product Service Systems (PSSs), Sustainable Manufacturing, Service CAD.

1 Problem statement

The modern world is evidently affected by an intrinsic limit of sustainability. The limits and the weaknesses of this model have been already addressed and highlighted in many occasions, by academics as well as by politicians, starting more than 20 years ago (e.g. the well-know and often cited Brundtland Commission in 1987). Fortunately, in the recent years, thank to the pressure of Western Countries (Europe *in primis*, followed recently by the U.S.A. with the new President), Sustainable Development (in its wider sense, from the environmental, to the economic and to the social perspective) has acquired a relevant part of the scene and many actions are now on the table for enabling sustainability in our society. From a systemic point of view, sustainability is a matter of optimization in the use of available resources, which are used along the life cycle of a system. This optimization could be achieved with the collaboration of all the actors involved in the life cycle of the product (designers, suppliers, manufacturers, customers, recyclers, etc.), who can adopt sustainable practices. Obviously, designers and engineers are the main performers involved in the early stages of the life cycle, thus being the most important in terms of sustainability decisions during the design activity. Unfortunately, designers are often not aware of the processes / phases that the products they are creating will meet in their life, while process engineers have to manage a large amount of data and information, without having adequate tools for considering the implications of their choices in terms of sustainable impacts. Then, a general optimization for reaching a more sustainable condition can be obtained only by managing and accumulating 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. Since the '70ies, engineers are supported in their activities by computer aided (CAx) tools, for modeling components and products, test and simulate their behaviors in a virtual environment, and store the obtained results, accumulating knowledge, in common spaces and data warehouses. A common characteristics among all these tools and methods is their highly specialization to a specific issue or scope. In general terms, each of them (i.e. CAD, CAE, CAPP, DES) considers only a particular phase of the system life cycle, trying to obtain a good solution for a particular problem in a limited context. A common idea emerging from the experts is that new engineering methods can't continue this trend, but must take into account to offer optimized solutions for multi-objective problems in an extended context. Designers and engineers of the next decade, being pushed by emerging sustainability issues calling for a better allocation / utilization of resources, need to access to new approaches, which consider the life cycle of a system / product from the beginning, in the widest possible way (product features, but also service features). They need a new technique / tool for performing multi-objective analysis and tests, thus being able to simulate the entire life cycle of a product / equipment.

2 Theoretical Background and Research Gaps

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. Life Cycle Assessment (LCA)/Life Cycle Engineering (LCE)/ Life Cycle Costs (LCC)). These well-know methodologies are the basis of the life cycle design approach. Also simulation has acquired an important role during the life cycle design phase because it provides tools for evaluating the performances of a system in virtual environments. Business and design process simulation have been extensively studied in the past and lots of techniques, approaches and tools exist, that can be divided in:

- Business process modelling techniques: flowcharts, IDEF techniques, Petri nets, simulation (discrete-event simulation, system dynamics), knowledge based techniques (knowledge based systems, qualitative simulation), Role Activity Diagrams (RAD).
- Information systems modelling techniques: data flow diagramming, entity - relationship diagramming, state - transition diagramming (STD), IDEF techniques, Unified Modelling Language (UML).

For example, Discrete Event Simulation systems are based on passive (entities) and active (resources) elements, which interact among them along a process flow simulated for a due time period. This simulation technique has a low-medium level of abstraction, since the model might be defined with a high level of detail, for defining how passive and active elements interact. On the contrary, dynamics models, typically constructed using a top-down approach, have a higher level of abstraction. For example, System Dynamics can be used in analysing different scenarios under different conditions and uncertainties, in different types of systems. The match between traditional methods (LCC, LCE, LCA) and simulation is given by life cycle simulation.

From an analysis of 32 contributions of the last 10 years about life cycle simulation seems that the utilization of computer aided solutions able to implement a simulation of different phases of a product life cycle it's a common idea. Simulation is used: (i) to combine flexibility and costs of production (e.g. Nakano et al. [30]), (ii) to estimate financial and environmental revenues (e.g. Kobayashi and Kumazawa [21]), (iii) to reach ecological potentials while fulfilling economical constraints (e.g. Meier and Massberg [28]; Sakai et al. [33]), (iv) to get the overview of the social / environmental influences of the designed product (e.g. Sakita and Mori [37]), (v) to predict the effect on costs / risks of modifying design, to assist waste management, to model economics of component remanufacturing or reuse (e.g. Xie and Simon [51]). Referring to these works, 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 is generally used, from spreadsheets, mathematical software and programming languages to specialist computational packages. Many industrial examples of life cycle simulation refer to: (i) facility management (Takata et al. [44, 45, 46]), (ii) industrial robot manufacturing (Yamada and Takata [52]), (iii) welded joint ship structures (Aoyama and Nomoto [2]), (iv) airborne emissions of biomass-based ethanol products (Yu and Tao [54]) and (v) cement manufacturing (Gäbel et al. [12]).

The firsts simulation tools appeared in the second half of the '90ies as cost estimation. Considering that over 70% of the total life cycle cost of a product is generally committed at the early design stage (e.g. Asiedu and Gu [6]), it is easy to understand why simulation has been primary applied to estimate product costs. However, cost estimation depends on the integrated solution of this set of problems in the early concept design phase (e.g. Asiedu and Gu [6], Wong et al. [48]). 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. Wong et al. [48]). A great variety of situations to be modeled and types of data are found, what makes it very difficult to use standard software tools to perform analysis. 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 (as defined in Lipman and Delucchi [27]) is to use general-purpose or specific simulation software tools, but this choice introduce a trade-off between flexibility and optimization.

At the beginning of 2K, many authors (e.g. [32], [33], [45], [20], [28], [46], [21], [27], [51], [23]) raised also the awareness towards environmental issues. Many works implemented a 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. [5] defines a procedure to organize a system of environmental indicators to be simulated.

From 2005, the number of authors (e.g. [22], [38], [37], [10], [30], [49], [48], [47], [50], [13]) 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 dismiss. Valuable works are those of Komoto et al. [22, 23, 24], Wong et al. [48], Sandberg et al. [38], Finne [10], Hayek et al. [18], Nonomura et al. [31], Kiritsis et al. [20], Xiao et al. [49, 50], Wang et al. [47], Li and Liu [26] and Meier et al. [29]. These authors started to include in their simulation 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 product + services (generally defined in literature as Product Service Solutions, PSS). In parallel to the advent of life cycle simulation, the experts started to include in their simulation approaches also the role of product related services. For this aim were defined the concepts of Service/Product Engineering and Service CAD system. The first one, it's a discipline that considers the service (not the product) as key factor of the customer's value (e.g. Hara et al. [14, 15, 16]; Sundin et al. [43]; Harada et al. [17]; Yang et al. [53]). The second one, instead, it's a new technique for the creation of computerized tools supporting service design activities (e.g. Shimomura et al. [39, 40, 41, 42]; Arai et al. [3, 4, 5]; Boyonas et al. [7]; Sakao et al. [34, 35, 36]).

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

3 Research Questions

As it has been shown, there are some remarkable *Research Gaps* in the field of life cycle simulation tools, gaps that lead to the following *Research Questions*:

- How can be selected life cycle options and improved life cycle simulation systems in terms of modeling capability, accuracy, and easiness to use?
- How can new simulation approaches extend their use beyond usual product design and manufacturing phases also taking into account the product-related services?
- How can manufacturing and post-manufacturing activities support the conceptual design phase?
- How can product designers easily and quickly get the overview and the insight of the social and environmental influences of the designed products?
- How can new modeling paradigms match different software apports to get an overall optimized solution?

4 Work plan

With the last evolutions, the concept of Life Cycle Simulation (LCS) has been officially started. Including also the service issues, it is possible of virtually emulating the whole behavior of a product during its whole expected life cycle. Technically, this 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 Product-Service System. The vision is, hence, to develop a prototype simulation toolbox, in which the different components describing the product behaviour and the service operations can be put together easily and tested (shortly speaking, such a tool can be called PLCS, Product Life cycle Simulator). Using this tool, a company may evaluate what kinds 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 services to gain market share. The simulation tool should be composed by 3 main parts:

- A Product Simulator module, in which both physical laws and statistical product behaviour are used to virtually emulate 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 (Product Model) for each product. Such a virtual model will simulate the evolution of the life status of the product, generating individual service requests (e.g. a maintenance service to be provided after a fault).
- A Services Simulator module, in which different service solutions related to the product-service needs are modelled. Such a library could be build upon an ontology of product-services by putting together models of individual services made of discrete resources involving both physical and statistical description and behaviour. 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 in which all previous components are integrated. After integration, various product models can interact with a given services solution allowing the product-service solution to be emulated and experimented in a virtual environment. The emulation of the product-service solution is allowed by a simulation engine (based on discrete event simulation) also working within the Integration Platform.

5 Expected results

The aim of this work is to create a new approach to product-service life cycle simulation. The aim is to model each product as an individual entity (and not as a family, or product type, as simplified in the work 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 modelling and is made up of components (modular solutions) that, joined together, create the service model needed. 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, will be developed a dynamic and realistic view of the service network activity 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 product - service solutions 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 Discrete Event Simulation for the virtual emulation of a service network could offer a good apport to engineers and designers of the modern companies to develop a comprehensive Product Service Solution (PSS) and not just to design a mere artifact.

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