Life cycle simulation: a state of the art analysis

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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, Life cycle engineering and costing, Product Service Systems (PSSs), Sustainability.

1 Introduction

The modern world is evidently affected by an intrinsic limit of sustainability. The current development model is based on a continuous cycle of production / consumption / dismissing, pushed by a global competition, in which companies can survive only providing new products and new solutions for satisfying the growing global demand. 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 [34]). 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.

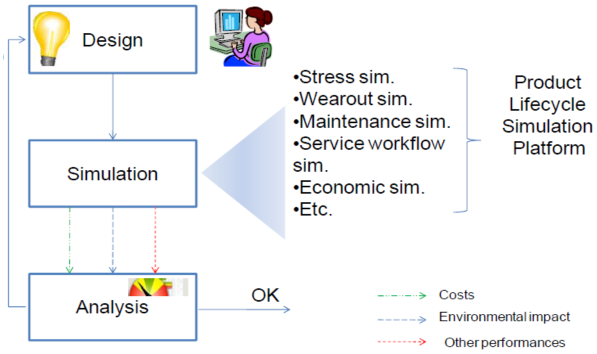
From a systemic point of view, sustainability is a matter of optimization of the use of available resources, which are used along the life cycle of a system (e.g. a car or a cloth, but also a production machine or a plant). This optimization could be achieved with the collaboration of all the users of the system that are distributed along its life cycle (e.g. the driver of a car, as well as its service technician), who can adopt sustainable practices (e.g. driving slow, recycling oils). A part these users' practices, the instantiation of such an optimization is evidently in the hands of the engineers that are in charge of the system design and development: it is up to designers and planners to find solutions for creating a less polluting car, like for using eco-friendly and energy efficient production processes, and also for implementing new services enabling more sustainable customers' behaviors. 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. In the design activity, such a deep knowledge is obtained following the typical process of knowledge capture, accumulation, and reuse. Designers and engineers accumulate their knowledge with a scientific method: they formulate their solution (one or more), they test it, analyze the results, and then keep the decision.

Since the '70ies, engineers are supported in their activities by a plethora of 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. For example, 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. Similarly, lots of CAE (Computer Aided Engineering) tools adopts extensively different simulating approaches, supporting designers in their tests and experiments; for example, the Finite Element Method and Analysis (FEM/FEA) and all related applications to material stress, fluid flow and heat transfer, became in the last 15 years very well known and applied desktop tools for testing and prototyping physical components, by simulating their behaviors under realistic conditions. Similarly, systems for CAPP (Computer Aided Process Planning) are already existing for supporting production engineers in the definition and simulation of manufacturing and assembly processes, while Discrete Event Simulation (DES) has been widely adopted for manufacturing plant design, as well as for supply chain dimensioning and definition.

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 a multi-objective problem in an extended context. The designers and the 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 ableto simulate the entire life cycle of a product / equipment (**Figure 1**). This is what the present paper wants to prove with a brief state of the art analysis.

Figure 1. Life cycle simulation as new tool for the designers of the next decade



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. For example, Life Cycle Analysis and Life Cycle Engineering (LCA / LCE) are two linked methodologies for the study of environmental aspects and potential impacts from the raw material acquisition to production, usage and disposal (e.g. Jensen et al. [23]). Also Life Cycle Cost (LCC) is a well-known technique (e.g. Korpi and Risku [24]), defined by the Japanese in the mid of the '90ies, and based on the cost of ownership for the customer, which aims to reach a balance between price and performances provided.
These well-know methodologies are the basis of the life cycle design approach. They are used (i) to conduct a deep analysis of the different stages of the product life cycle, accumulating product knowledge, and (ii) they can be used to define different scenarios related with the product life cycle.

In the literature it is already possible to find some reference works directly related to product life cycle design and simulation, as shown in **Table 1**. This table classifies 32 contributions of the last 10 years in 3 different clusters, based on the nature of the research : (i) Conceptual work, (ii) Technological contribution, and (iii) Experience report. The Conceptual cluster includes papers which explain the need of the life cycle simulation and discuss the state of the art on possible methods to be adopted. The Technological cluster includes contributions that make a point on new technologies and software tools useful for life cycle simulation. Finally, “Experiences” papers report real implementations / experiments of life cycle simulation within industrial companies.

Table 1. State of the of life cycle design and simulation

Author	*Conceptual cluster*	*Technologica cluster*	*Experiences*
[1] Asiedu and Gu	X		
[2] Nonomura et al.		X	
[3] Oscarsson and Moris	X		
[4] Sakai et al.	X		
[5] Takata et al.	X		
[6] Kiritsis et al.		X	
[7] Meier and Massberg	X		
[8] Takata et al.	X		
[9] Kobayashi and Kumazawa	X		
[10] Lipman and Delucchi			X
[11] Xie and Simon		X	
[12] Komoto and Tomiyama		X	
[13] Komoto et al.	X		
[14] Sandberg et al.			X
[15] Sakita and Mori	X		
[16] Finne	X		
[17] Nakano et al.	X		
[18] Xiao et al.		X	
[19] Wong et al.			X
[20] Wang et al.		X	
[21] Xiao et al.		X	
[22] Gonçalves and Siqueira		X	
[24] Korpi and Risku			X
[25] Fleischer et al.			X
[26] Hayek et al.			X
[27] Cameron and Ingram			X
[28] Takata et al.			X
[29] Yamada and Takata			X
[30] Aoyama and Nomoto			X
[31] Aiyoshi and Maki			X
[32] Yu and Tao			X
[33] Gabel et al.			X

The utilization of computer aided solutions able to implement a simulation of different phases of a product lifecycle can be traced in all the quoted works. Simulation is used: (i) to combine flexibility and costs of production (e.g. Nakano et al. [17]), (ii) to estimate financial and environmental revenues, taking the form of a decision tree to quantify the uncertainty of various business scenarios (e.g. Kobayashi and Kumazawa [9]), (iii) to reach ecological potentials while fulfilling economical constraints, given the dependency on specific products (e.g. Meier and Massberg [7];

Sakai et al. [4]), (iv) to easily and quickly get the overview and the insight of the social and environmental influences of the designed product (e.g. Sakita and Mori [15]), (v) to predict the effect on future costs or the risk of modifying design, to assist waste management using the output graphs of disposed components or products, to model economics of component remanufacturing or reuse (e.g. Xie and Simon [11]). Summarizing, a simulation is generally implemented for evaluating two main issues: (i) product life cycle related costs, and (ii) product life cycle related environmental impacts.

There are different industrial applications of life cycle simulation described in literature. In accordance with the survey of Cameron and Ingram [27] on process modeling across the life cycle, the most common reason for modeling, in 95% of cases, are providing insight 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 works LCC, LCE and LCA methodologies are applied together, supported by a simulation tool used to test and estimate different scenarios. A wide range of tools is generally used, from spreadsheets, mathematical software and programming languages to specialist computational packages. Many examples of life cycle simulation refer to facility management. Takata et al. [28] have developed an information infrastructure for facility 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. The same concepts, but in the industrial robot manufacturing, can be analyzed in Yamada and Takata [29], where a life cycle simulation method is described. Another method is presented in Aoyama and Nomoto [30], where life cycle simulation is used 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. There are also some interesting applications of life cycle assessment and simulation of airborne emissions of biomass-based ethanol products (e.g. Yu and Tao [32]) and for simulating environmental performances, product performances and cost in cement manufacturing (e.g. Gäbel et al. [33]).

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 [1]), 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 [1], Wong et al. [19]). 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. [19]). 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 [10]) is to use general-purpose or specific simulation software tools, but this choice introduce a trade-off between flexibility and optimization.

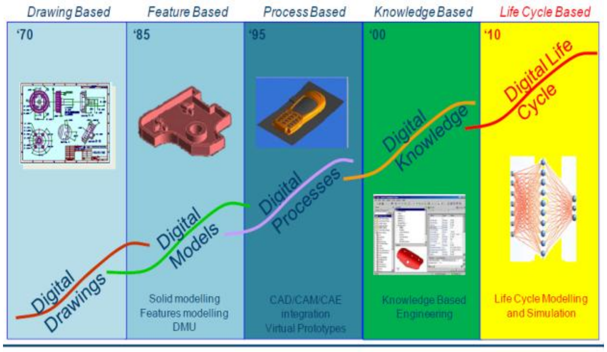
At the beginning of 2K, many authors (e.g. [3], [4], [5], [6], [7], [8], [9], [10], [11], [12]) raised also the awareness towards environmental issues. Many works implemented a simulation for assisting designers in forecasting possible future strategies, environmental impacts and costs associated with 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. [13], [14], [15], [16], [17], [18], [19], [20], [21], [22]) 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. [13], Wong et al. [19], Sandberg et al. [14], Finne [16], and Hayek et al. [26]. These authors have 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). For example, Wong et al. [19] present the "Design for Service" 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. Sandberg et al. [14] describe a model for cost prediction that introduce evaluation of post-manufacturing activities in the early concept designs phase for hardware parts of functional (including both hardware and service) products. In the tooling machines sector, Hayek et al. [26] present a simulation model allowing maintenance and replacement decisions. Above all, Komoto et al. [13] define a simulation model for the specific description of systematic forms of PSS, to be used to evaluate and compare alternative PSS solutions from environmental and economic perspective. In a previous work (Komoto and Tomiyama [12]) the same authors 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". This prevents the designer from overlooking potential solutions and helps systematically optimize design using life cycle simulation. Similar works are the study of Nonomura et al. [2] on simulation approaches for configuring modular products, the PROMISE project (e.g. Kiritsis et al. [6]), and 3D (e.g. Xiao et al. [18]; Wang et al. [20]) and 4D (e.g. Xiao et al. [21]) modeling frameworks for complex product virtual prototyping management and service-oriented simulation.

3 Conclusion

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. This is already enabling a new wave in the virtual prototyping solutions: from digital drawings and models to digital life cycle (**Figure 2**).

Figure 2. The new wave of virtual prototyping: digital life cycle



Even if simulation methods and tools are more flexible and easily adapted to problems with this level of complexity, its use is not free from shortcomings. The reason lies on differences among practical situations that are difficult to anticipate during the software development phase. These differences often require model and data modifications and, consequently, good simulation software with this capability. In particular, Life Cycle Simulation is system depending. For the most part of the systems, products owned by final customers (like a car, or any other objects), product LCS might deals with its functionalities and services that might be provided to the customer. In other contexts, like a manufacturing system, LCS might deal with the system capabilities, which have generally a long life cycle, and maintenance services. A reference ontology / methodology is probably needed to clearly define the different elements which compose the concept of Life Cycle Simulation. With this common basis, it will be probably possible to instantiate new flexible simulation environments, for giving to the planners and designers of the next decade new simulation tools for supporting their innovation process, enabling the development of more sustainable products and services.

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