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Product Concept Manufacturability and Sustainability Assessment with Eco Process Engineering System

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Abstract The focus of engineering design on achieving a superior product, processes or services from functional and economical factors is now shifting towards sustainable design which considers environmental, economical and social aspects. This can be achieved by integrating the sustainable elements into the engineering design and analysis tasks throughout the product's lifecycle. Life Cycle Thinking (LCT), Design for Environment (DfE), eco-efficiency, eco innovation should be part of collaborative product development. In the development of products, product improvements, processes and related services, e.g. product service systems (PSS) which provide customer and business value but significantly decrease environmental impacts, new tools are needed. Eco-process engineering system (EPES) is the methodology and related ICT tools provided as a service for the development of PSS. The goal is to improve eco-efficiency, i.e. reduce energy and resource consumption, emissions, and the use of hazardous substances through the holistic analysis of PSS and its life cycle. European research project, EPES, carries out research and development to improve the sustainability performance of end-users operations, products and services. EPES system integrates existing tools and provides them as configurable services for non-ICT experts. This paper shows a case study for conceptual product assessment using EPES system.

1. Introduction

The definition of sustainability in the Report of the Brundtland Commission report [1] is well known: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs". Sustainability is built on three pillars: economic, environmental, and social sustainability. As sustainability covers a broad area of different aspects, it is very difficult to make it measurable. Sustainable innovation wants to achieve improvements by the integration of economic (Profit), environmental (Planet) and social (People) concerns. Sustainable Manufacturing has been defined by the U.S.

Department of Commerce [2] as: “The creation of manufactured products that use processes that are non-polluting, conserve energy and natural resources, and are economically sound and safe for employees, communities, and consumers.”

Eco-efficiency has been defined by the World Business Council for Sustainable Development (WBCSD) [3]: "eco-efficiency is achieved by the delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life-cycle to a level at least in line with the Earth’s estimated carrying capacity." WBCSD pointed out that high eco-efficiency products or services can be achieved through improving seven key eco-efficient elements as shown here (REDUCES, in short) [3]. 1. **R**educe material intensity; 2. **E**nergy intensity minimized; 3. **D**ispersion of toxic substances is reduced; 4. **U**ndertake recycling; 5. **C**apitalize on use of renewable resources; 6. **E**xtend product durability, and 7. **S**ervice intensity is increased.

To summarise those definitions; sustainable development, sustainable manufacturing and eco-efficiency: “Creating more value with less environmental impact” – doing more with less. Thus engineers and managers need to identify possible improvements to goods and services with lower environmental impacts across all life cycle stages. New ISO 14045:2012 standard, on environmental management, shows principles, requirements and guidelines for eco-efficiency assessment of product systems, and enables the study of life-cycle environmental impacts of a product system along with its system value for a stakeholder.

Life Cycle Thinking (LCT) is a management philosophy for that and it has been adapted to European Commission policies [4]. With LCT, shifting of potential environmental burdens between different life cycle stages can be recognized. This helps to avoid local optimizations that simply transfer burdens to other stages. Life cycle thinking should be integrated as a part of any new material or product development already at the early stage of the development. LCT can be applied without going into details of a full Life Cycle Assessment (LCA) study [5]. LCA is used in assisting the engineer in the product design but possess drawbacks. Conducting LCA according to ISO 14040 standard series requires special expertise and large amounts of data, and is usually time-consuming. To conquer these challenges, simplified, automated and understandable tools and methods are needed in order to guide the designer in developing sustainable products, processes and services. These are also the goals of the EPES project [6].

Virtual factories, e.g. extended enterprises with multiple stakeholders and actors, are the current way of working in the development of technical Product Service Systems (PSS). Creation of customer value by integrating products and services in a distributed organization creates new challenges in communication, process management and knowledge management. Service-oriented ICT tools are one enabler for efficient networking and the PSS development. Due to increased system complexity, distributed multidisciplinary engineering is often required. Easy-to-use tools are needed to enhance the efficiency, transparency and traceability of such multidisciplinary optimisation and decision-making processes. Business process management (BPM) of the multiple engineering processes is also required to orchestrate the activities carried by the various actors.

The design phases of most products, processes or services are often determinant for the sustainability and environmental performance throughout their life cycle. The majority of environmental impacts will be determined during the design phase. The environmental impacts of products can be significantly reduced through optimised design. Another issue is how the well the product or process is operated, managed and maintained, but this is not covered in detail in this paper, even though the functionalities of the EPES system [6] cover some of these product aspects as well. The overall essence of the EPES system concept is to evaluate PSS lifecycle environmental impacts, eco-efficiency, and to maximize the value of the performance of PSS, i.e. to improve their ability to do more with less.

2. Product development with eco-efficiency aspects

The focus of engineering design on achieving a superior product, process or service, from the currently prevalent point of view of functional and economic factors, is now shifting towards sustainable design. Sustainability-related issues are increasingly important in business decision-making. Examples of the drivers of this development are:

- Cost savings, resource efficiency
- Society-set regulations, directives, standards, etc.
- Customer requirements, business reputation

The number of regulations that are related to sustainability has been steadily growing, presenting new legal obligations to industry. Enterprises are also becoming increasingly aware of the importance of being able to credibly present facts about the sustainability of their performance to the public, which is increasingly aware of its importance. The aim of the EPES system [6] is to move from typical goals, i.e. functionality and cost, to several simultaneous goals, i.e. sustainability.

Typical sustainability targets, or eco-efficiency objectives, often self-reported by manufacturing enterprises [7, 8, 9], are:

- Energy-savings, (electricity and fossil fuels), including increased use of renewable energy sources
- Reduced carbon dioxide (CO_2) emissions; other emissions, like volatile organic compounds (VOC)
- Reduced the fresh water usage
- Reduced raw material consumption, reduced amount of waste
- Workplace safety, zero work-related accidents

In addition to the ones presented here, there are many more objectives, parameters and key performance indicators (KPI) used in industrial decision-making.

2.1 Decision making with advanced modelling and simulation

As most decisions that affect sustainability need to be made in the design stage, at which actual measurements cannot yet be made, simulation is a crucial tool for evaluating the forthcoming effects of the design decisions in the following life-cycle stages. Advanced modelling and simulation requires special expertise, and multi-disciplinary modelling is often necessary in order to take into account all the various aspects of sustainability. This creates a need for efficient co-operation between analysts of various backgrounds.

Traditionally, engineering processes are affected by manufacturing knowledge and product performance-oriented factors. However, nowadays this traditional concept of performance needs to be extended into a wider meaning, with sustainability being one of the main factors. The contribution is not only at the level of the end product, but also applies to the manufacturing systems that are used for producing the product. Eco-constraints need to become a part of the wider assessment of the overall product feasibility analysis. This analysis needs to consider not only traditional cost and productivity-oriented parameters, but also eco-constrains that are derived from all the relevant stages in the product's whole life cycle.

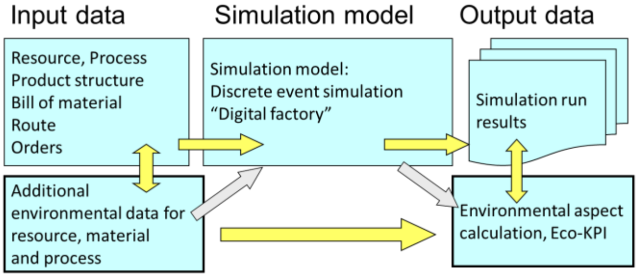

Figure 1. Connecting eco-KPI calculation to simulation, based on [10].

Manufacturing and production system simulation can be enhanced by taking into account sustainability aspects. Some commercial DES (discrete event simulation) software applications already support energy consumption and related CO_2 emissions modelling, for example as presented by Heilala et al [10]. Sustainability KPIs can be calculated by combining the simulation results with product, process, resource and related environmental data (see Figure 1). The results typically consist of sustainability accounting data, i.e. environmental inventory data, which can be used for the calculation of predictions of sustainability or eco-KPIs. For the full environmental impact analysis, proper LCA tools and experts are required.

2.2 Multi-objective and multidisciplinary optimisation

Selection of the best design among a set of alternatives is a very important task in the development stage of a product or process. Introduction of multiple criteria and constraints to be considered increases the complexity of a decision-making process. As sustainability cannot be limited to a single stage of the life-cycle of an industrial product, it is always a very complex issue, and presents a need for complex multi-objective decision-making, in which compromises need to be made between mutually exclusive criteria. This also greatly increases the quantity of good-quality data that is needed to be presented to decision-makers.

3. EPES System – a new way of working

The EPES project (www.epes-project.eu) is developing a comprehensive software platform that allows engineering issues to be addressed from the point of view of sustainability. The EPES system is an integrated process-management platform that provides general advantages as an engineering and/or decision-making platform. Its focus is on efficient inter-disciplinary co-operation, communication, data collection and management. It also serves as a tool for communicating information from the engineering community to the strategic decision-makers, allowing them to make informed decisions at the earliest stages of the product, process or service development.

The EPES platform combines both data and procedures—both human and computer—into a package that allows its users to both codify and automate the various tasks that are necessary for addressing complex issues like sustainability. By using business process management and simulation automation techniques, the platform streamlines analysis processes by reducing repetition, especially in set-up tasks. Automating simulation and numeric optimization tasks also help to ensure that the outputs from a set of similar analysis tasks are consistent and thus easily comparable.

Instead of directly addressing sustainability, the main focus of the platform is on streamlining the processes that are necessary for addressing it. In practice, by reducing the amount of required effort, the application of the solution also results in more sustainable outcomes, by allowing the enterprise to more efficiently use the available engineering resources, both human and computational.

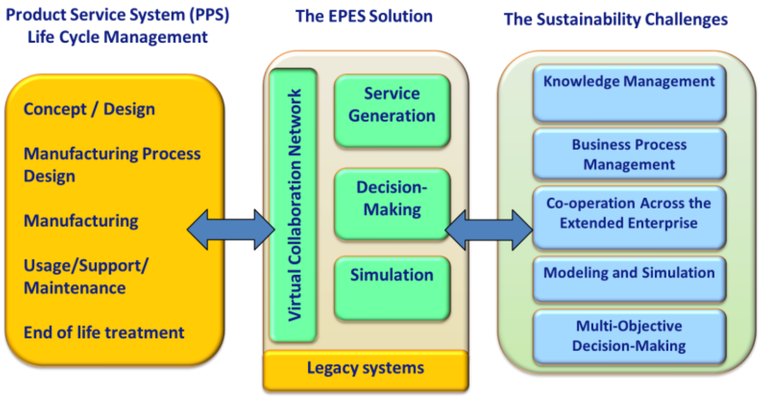

Figure 2. EPES System simplified.

EPES project objective is to develop a novel eco process engineering system based on the Business Process Management (BPM) approach, which will constitute a comprehensive process-oriented platform, enabling dynamic composition of services, so called EPES Services, that are adaptable to different products and operating conditions. The EPES solution will also support continuous improvement of processes and products in operation along the life cycle, applying optimization and simulation strategies for the operating phases and for improving future product designs.

The EPES platform makes use of many existing solutions as parts of its integrated comprehensive platform. Additional software components have been developed in order to facilitate the integration of these existing solutions. These solutions include:

- **Alfresco**: An Enterprise Content Management (ECM) system
- **Activiti**: A business process modelling and execution framework
- **SOMO by ESTECO**: An optimization and simulation integration platform
- **Pentaho**: A business intelligence platform

The key software modules of the EPES solution are (see Figure 2):
• ***Virtual Collaborative Network (VCN)***: A collaborative Enterprise Content Management and communication platform, which allows the tracking of business optimization opportunities and the discovery of eco-constraints and objectives through a networked business infrastructure. It also provides collaborative web

content, document content management capabilities and business process workflows execution capabilities, enabling human interaction.

• ***Service Generator (SGM):*** A tool for configuring EPES Services, deploying them, to provide a web-based UI cockpit to access to the EPES solution, and capabilities to connect the EPES Services to the VCN workflow, bridging the gap between business and IT layers.

• ***Decision Making Module (DMM***): A platform that allows decision-makers to optimize and analyse different engineering and business processes through dedicated tools.

• ***Simulation Module (SM):*** A tool to facilitate the set-up and execution of external simulation tools in order to provide data for calculation of to-be key performance indicators (KPI).

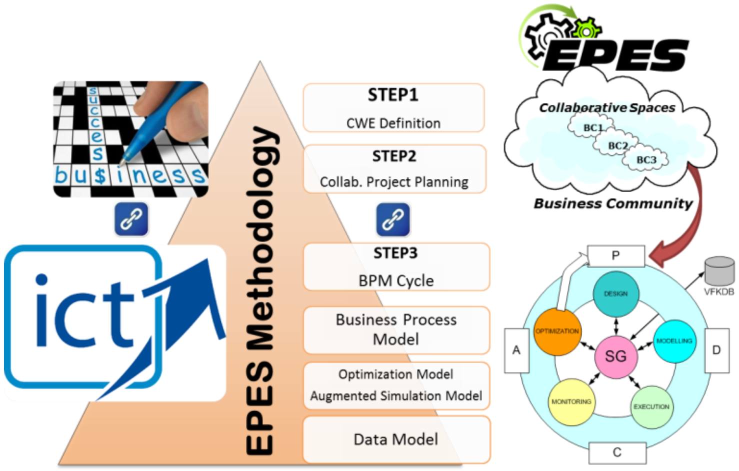

Figure 3. EPES Methodology main steps.

The main steps in the EPES methodology (see Figure 3)

1. Collaborative work environment definition
2. Collaborative project planning
3. Business Process management cycle, PDCA

The EPES system is a collaborative work environment (CWE) and a portal to a product service system (PSS) -based ecosystem. This work environment can be extended beyond the group of people who directly participate in the development processes. This enables, for example, a more direct form of feedback from the users to the engineers.

Each of the actors in the defined CWE system has a role. The role could be, for example, an owner of the product, a user of the product, a service provider, a manufacturing or product-related engineer, a sales representative or a business decision-maker. Using the collaborative parts of the EPES system, any group of actors in the product service system community can distribute knowledge, collaborate, pin-point eco-constraints, bottlenecks and solve problems.

4 Conceptual phase product DFMA and sustainability assessment

For an assessment of the sustainability of a product design, the overall product sustainability performance is the ultimate criteria. The process or manufacturing system assessments are only its sub-elements. To be specific, the sustainability assessment of a manufacturing process would not cover the other phases of the life-cycle of a manufactured product. An optimized manufacturing process does not necessarily mean that the product itself is optimal, considering its sustainability performance. On the other hand, to achieve an optimal overall sustainability performance while designing a product, the corresponding manufacturing processes and resources need to be optimized based on some sustainability criteria.

In one of the industrial demonstrators of the EPES project, the aim is to create a simulation and optimisation service for non-ICT experts dedicated to the early product and manufacturing system design phase. The aim is to compare design concepts for aircraft wings and to optimise both the product and its manufacturing system (i.e. future factory concept). The targeted users are people from multiple engineering disciplines: product architect, aeronautics, materials, structural, load, cost, manufacturing, etc.

The EPES system will support users to make informed decisions on the performance of design concepts from the eco-efficient manufacturing perspective using manufacturing simulation and optimisation. The EPES system has been set-up to integrate the assessment of traditional manufacturing KPIs such as production rate, resource utilization, waiting times, work in progress, with those related to the sustainability of the production processes, e.g. energy consumption, CO_2 emission etc. The essential questions answered through this assessment are:
• Productivity KPIs: What production rate can be achieved for a design using a given set of pro-cesses and resources?
• Sustainability KPIs: What are the energy consumption, the emissions and the hazardous material waste resulting from the manufacturing for a design using a given set of processes and resources?

Simulation parameters include the list and number of resources and processes, product routing and cycle times, factory calendar and work shifts, required tooling etc. The EPES system provides optimization services to find out optimum value of any of the parameters while some other parameters are set constant and some results are set as defined objects, i.e. optimum number of resources to reach defined capacity. The optimisation engine is based on the SOMO solution from ESTECO and the simulation engine used in the demonstrator is GeSIM from VTT.

The SOMO platform has been developed for automating simulation tasks that have a relatively small and static set of parameters. In order to expand the possible uses of SOMO, the EPES platform includes tools that automate some of the manual tasks that are involved in setting up an optimization task (Figure 4). These tools allow the configuration of an optimization task to be performed automatically for a set of similar models that include a variable number of objects, each with its own set of associated input and output parameters.

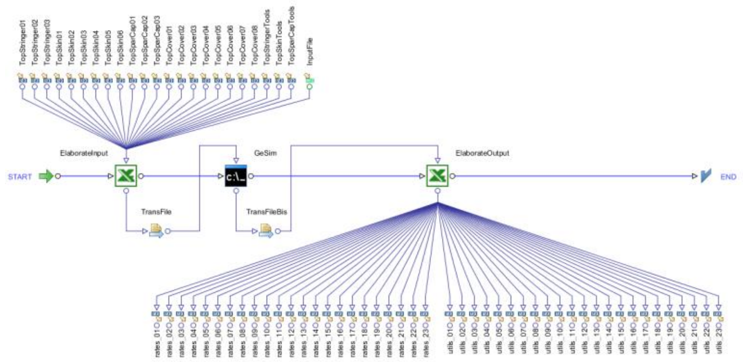

Figure 4. A high-dimensional automated simulation workflow in SOMO, created by tools in the EPES platform without user intervention.

This combination of tools allows the users to perform an optimization of any manufacturing concept on a powerful server, using a browser-based user interface or as an automated task in an executable business process flowchart model, without any of additional manual tasks that are usually required for such analysis tasks. No input or output data for the simulation needs to be downloaded from the ECM system. Instead, it is directly accessed from the repository by the optimization and simulation tools. The simulation results are automatically stored in a human- and machine-readable form in the ECM system.

5. Discussion and Conclusion

Ensuring the sustainability of manufacturing requires an integrated systems approach and spans technical, economic, ecological, and societal issues. Interactions within and across these issues are critical to the fundamental understanding of sustainable manufacturing, because focusing on any single issue alone could result in a suboptimal solution or other unidentified consequences. Industry recognizes that (1) sustainability challenges in manufacturing can only be addressed through multi-disciplinary methodologies and (2) implementing these methodologies can have significant economic benefits for sustainability in general, and sustainable manufacturing in particular [11].

In order to reduce the environmental impact of a product under development, designers must have suitable information made available with a reasonable effort. If they do not feel that the information is suitable or can be utilized with a reasonable effort, they will not make use the information, nor the method for deriving it [12]. When developing products, designers have to consider the consequences of their decisions in a number of fields ranging from economy, reliability and ease of change to the environmental impact. In most engineering environments, designers need to be encouraged to integrate environmental aspects by increasing the availability of suitable tools and knowledge. In short, the main requirements should include: A simple and easy to use method; Availability of appropriate data; Clear and easily communicable results; and Traceable conclusions. Above all, any tools or information deployed as part of Design for Environment (DfE) should be fully integrated in an existing design process, procedures and manuals. Environment should become a new key parameter to consider in decision-making, alongside technical performance, safety and cost [12].

The connections between products, processes and manufacturing systems are becoming more complex. Sustainability-related issues are important and they are adding heavily to the complexity of the design process. The amount of data that is needed for decision-making is growing and multiple parameters and constraints must be considered simultaneously. Digital Manufacturing methods, i.e. simulation & modelling are useful for analysing the product and production system both from the point-of-view of traditional performance measures such as productivity, efficiency, cost etc. and the point-of-view of sustainability-related performance measures (see Figure 1). Because multiple engineering disciplines and multiple life cycle stages are involved in the goal of sustainability, multidisciplinary optimisation (MDO) and multi-objective optimisation (MOO) techniques can seldom be avoided. When these techniques and tools are provided as services, the transparency and traceability of the decision making processes can be improved.

Provision of engineering analyses, optimisation and simulation as services, e.g. automation of an engineering analysis processes using cloud computing, is one of the advantage of the EPES platform. When combined with knowledge management, communication and collaboration, business intelligence, and business process modelling and execution, a comprehensive platform is created for tackling the comprehensive problems of sustainability.

Benefits and challenges found during EPES early prototype testing are shown in Table 1.

Table 1. Benefits and challenges in the case study

Nr.	**Benefit**	**Challenge**
1	Integration of engineering disciplines and methods, traditional productivity and sustainability assessment for ***early DFMA (Design for Manufacturing and Assembly) analysis***	Data harmonisation and integration of existing legacy systems. Tool and data interoperability to orchestrate heterogeneous methods and systems to support the business case
2	To ***predict the performance of a manufacturing system*** considering both productivity and ecologic performance	The accuracy of data in the early design phase. Integration of environmental and productivity indicators in a single environment
3	Automation of engineering task, fast analysis cycles. To transform ad-hoc simulation studies into ***service oriented capability*** by exploiting EPES architecture	Development of service oriented analysis for non-simulation experts. Fast and adaptive decision support implemented and usable to industrial practitioners

The EPES project is still an on-going work. A prototype of the EPES system has been built. The integration, assessment and demonstration phases start in 2014. The assessment of a PSS with the EPES System can guide the development towards more sustainable solutions and provide information on the aspects that require further study. Instead of several desktop applications, engineering islands of analysis, the EPES system provides both integration and automation of the assessment methods that are necessary for tackling sustainability. More details on EPES also in [13].

EPES system can cover whole product service system lifecycle, eco-efficient solutions:

- Optimized performance by design
- Dissemination of best environment practices within the supply chain, virtual collaboration network
- Greener manufacturing processes
- Supporting efficient product operations
- Recycling and re-use at end-of-life

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