Environmental Assessment Methods of Smart PSS: Heating Appliance Case Study

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Abstract. At the heart of industry 4.0, industrials are developing integrated offers of "Smart Product-Service Systems". Many industrial firms are moving toward product-service systems (PSS) due to their capacity to involve value systems, business models, boundary spanning, dynamic capabilities, and other factors leading to reduced environmental impacts. In this paper, we introduce an easy-to-implement method to evaluate Smart PSSs applied to residential heating systems. Our approach is based on existing environmental assessment methods (focus on Life Cycle Assessment) and accounts for resource consumption, toxic and greenhouse gas emissions as well as waste generation. On the other hand, it also considers different features of the circular economy including the upgradability of Smart PSS offerings and end-of-life heating systems.

Keywords: Environmental assessment, Product-Service-Systems (PSS), Life Cycle Assessment (LCA), Upgradability (UP), Heating Systems

1 Introduction

The latest trends in industrial development show that firms are moving from product-driven businesses to service-oriented logic [1] through Product-Service systems (PSS). Doualle et al. [2] introduced PSS as one of the solutions for companies to maintain their competitiveness while overcoming the sustainability challenge. With the advancement of artificial intelligence (AI), and information and communication technologies (ICTs), items have grown more intelligent by adding smart components leading to the recent concept of smart PSS. The term smart PSS mainly refers to a PSS based on "networked smart products and service systems for providing new functionalities "[3] thus leveraging on digital infrastructures, the Internet of Things, cloud computing, and analytics [4] and making possible Digital Servitization strategies [5]. In recent years, public authorities, environmental experts and organizations, and other stakeholders have become increasingly interested in the environmental quality of industrial solutions. The PSS environmental assessment has a special interest because PSS are widely claimed to reduce environmental impacts while maintaining, transforming, or even adding to user satisfaction [6]. Consequently, this research aims to configure and adapt the predominant LCA method to make it applicable to smart PSS, then to test this proposal on an industrial case in the heating appliance field to study its limitations. The paper is structured as follows. Section 2 provides an investigation on similar methods used in the literature. Section 3 defined the method of LCA procedure configuration for smart PSS. Section 4 presents a case study in the field of heating appliances. Finally, the main findings of this paper and recommendations for future work are presented in Section 5.

2 Smart PSS environmental assessment: literature review

PSS is an interdisciplinary research field, which attracts many different points of view and contributions. The concepts, definitions and typologies come from distinct complementary areas. Typically, business management investigates the bundling of products and services to form solutions. A well-recognized definition in this area considers PSS as “a system of products, services, supporting networks and infrastructure that is designed to be: competitive, satisfy customer and needs while assuring lower environmental impact than traditional business models” [7]. The growing interest in the digital transformation of industrial firms has prompted academic interest in incorporating technology-based research into traditional PSS subjects of study [8]. Service propensity and digitalization are closely correlated and even mutually enhance each other. Accordingly, the notion of "Smart PSS" is presented as the accompanying digital technologies to provide new functionalities to meet individual customer needs successfully and in a sustainable manner. Examples include remote product monitoring, remote diagnostics, predictive maintenance, or equipment optimization based on operational data [5]. This leads to the concept of Upgradable PSS, which is introduced as ‘an offer model providing an integrated mix of products and services that are together able to fulfill a particular customer demand, based on innovative interactions among the stakeholders of the value production system, where the economic and competitive interest of the providers continuously seeks environmentally and socio-ethically beneficial new solutions’ [9].

2.1 Life cycle assessment for smart PSS

Andersson et al. [10] compare 12 environmental methods and present LCA as one of the most relevant methods for service systems. In addition, LCA is structured by ISO standards and recognized by [11] as the key reference method to evaluate the environmental impact of PSS. With LCA, one can explore all of the many forms of environmental consequences of a system, with two primary applications: (i) analyzing the impact of several life cycle phases on overall environmental load in order to prioritize improvements on products or processes; and (ii) comparing the environmental impact of various product systems [12]. The LCA was not established for the PSS context, thus its application to this particular context requires an adaptation [13]. LCA is a tool for comparing the environmental impacts of systems that perform the same function. Thus, comparisons are made based on Functional Units (FU) within a specified scope. The definition of this functional unit is one illustration of this need for adaptation. Indeed, LCA was essentially designed for the assessment of the environmental impact of a product or service and not of a system comprising both products and services such as the PSS. It will then be necessary to be particularly vigilant in the definition of this FU. In addition, the definition of the FU is a crucial step because it is closely linked to the definition of the scope and therefore the result of the evaluation [2]. Other concerns encountered during the application of the LCA method in the PSS have been the level of uncertainty due to the hypotheses taken into account by the integration of services into the product system. Moreover, the smart concept of PSS also carries difficulties in the environmental evaluation of the ICT systems. This research focuses more on ICT environmental impacts, the need for upgradability, and uncertainty analysis.

2.2 Specificities of LCA for smart PSS: ICT and upgradability

The article focuses on Smart PSS where 'smart' dimension indicates the presence of a set of ICT systems. This leads to investigate more specifically the environmental impacts of the components integrated in a new model perimeter such as the ICT and UP modes. Literature sources indicate that ICT has both direct and indirect environmental impacts, including water, air, soil pollution, and natural resource. Berkhout and Hertin [14] have classified the environmental impacts of ICT into three main categories:

- (i) First order impacts (or direct impacts) on the environment caused by the production and use of ICTs on the environment.
- (ii) Second order impacts (or positive indirect impacts) which are concerned with the impact of ICTs on economy structure, production processes, and their associated distribution systems.
- (iii) Third order impacts (negative indirect impact) in which ICT plays the role in promoting structural change and economic growth [15].

Performing the LCA of an ICT network is very challenging. As a result of telecommunication and Internet services, which are globally connected and some national nodes are accessed by several operators, description of a national ICT network is complicated in terms of both scope and allocation. According to literature, due to study simplicity, effort, and relevance, more than half of all studies focused on only one or two impact types. Secondly, for ICT in particular, another reason for concentrating on just a few impact categories could be the limited access to relevant inventory data. The most typical impacts categories used to assess ICT environmental effect are global warming potential, energy or material demand/material depletion and cumulative energy demand [16]. Furthermore, the ReCiPe and CML methods were the most widely used throughout studies that investigated several impact categories. Another significant feature of Smart PSS is upgradability (functional improvements brought to a system over time) considered as the foundation of a new paradigm of consumption/production in order to satisfy at the same time the environmental sustainability notably due to the rationalization of materials use over time and the benefit of such systems for both clients and producers [17]. Khan et al., [18] defined upgradability as the potential aspect that might contribute to a product lifetime extension strategy, with an emphasis on PSS. Therefore, the term "upgradability" stands for an opportunity to provide an eco-design system, and this led to the eco-innovation methods identifying innovation axes to decrease radically the environmental impacts by considering stakeholder attractiveness criteria. In conclusion, LCA contains some limitations that require adapting its use to the design process. First, LCA focuses primarily upon quantitative environmental evaluation. Secondly, the functional unit reference does not efficiently deal with the user's needs. Thus, according to Trevisan, LCA should be coupled with eco-design approaches that are related to process planning or innovation methods [6].

3 Configuration of a LCA procedure for smart PSS

Specific recommendations for analyzing smart PSS environmental performance are still lacking in the literature and the limitations raised above remain uncovered. Life Cycle Assessment is a relatively new tool to analyze and assess the environmental impacts fully integrated systems embedding products, processes or services by multi-attribute systemic evaluations. This section aims to demonstrate how we configure the traditional LCA method to make it applicable to PSS: notably the capacity to represent a large variety of PSS added-values for any single PSS offering (by considering a notion of PSS scenarios); the ability to assess the impacts of upgradability; the consideration of ICT components; and the ability to check the uncertainty of assessment results. As described above, the LCA is a tool providing quantitative evaluation and consisting in different phases such as goal and scope definition, inventory analysis, impact assessment, and interpretation. Briefly, at the goal and scope definition stage, we seek to frame the life cycle analysis of the studied system. During the inventory phase, one must have a global vision of the resources used and the outgoing flows of products or services. In the impact assessment phase, the inventory of flows is translated into environmental impacts using modeling on LCA software. In the last phase, we interpret the results obtained in order to understand the multiple tables of figures and graphs that lead to the conclusions. It is sometimes necessary to carry out one or more sensitivity studies to refine its interpretation. One of the important questions of this research is whether it is possible to realize the adaptation of LCA to the PSS framework. According to us, the impacts of the PSS do not fundamentally dispute the methodology or LCA stages, but rather require more detailed work in configuring them to take into account the specificities. The life cycle analysis process consists of four main phases:

• **The goal and scope definition**: this stage needs particular attention due to the structured mechanism for defining PSS scenarios. The mechanism that we propose is to define scenarios based on two criteria: Differentiating the economic models and differentiating the "service packages" of PSS result in the existence of more than one function of a system. In order to deal with the multifunctional system from the FU point of view, the main function of the PSS is taken into account and the other functions of the Smart system are considered as secondary (functions of comfort, maintenance, etc.,) and therefore ignored. In our case, the FU must be the same for all scenarios, and it results in heating the rooms included in the living area of the building.

• **Life cycle inventory**: First, during this phase, we must carefully choose the database and allocation method that will be used. In terms of database selection, it is performed based on the input and output typology flow criteria. Furthermore, it is critical to determine if there are recycling items in the materials inventory, which indicates the necessity to apply allocation techniques such as Apos that offer a perspective, in which waste producers are incentivized to assess recycling and reuse possibilities due to the partial allocation of impacts to useful treatment products. These materials are not present in the system under consideration. As a result, the Ecoinvent v3.8 database (which includes inventories of the materials we are looking for) and the cut-off allocation technique were chosen for use in the OpenLCA simulation. Secondly, the life-cycle inventory has to take into consideration the notion of the PSS Scenario introduced earlier. Each scenario requires a specific inventory, while all scenarios share common data. The variety of PSS offerings necessitates the incorporation of particular inventory types. For instance, considering the inventory of ICT materials for Smart PSS scenarios.

• **Impact assessment**: specifically, this phase consists of defining the life cycle assessment approach and the characterization method. The attributional approach is therefore applied since the study focuses on comparisons of different PSS scenarios, each characterized by the same indicators. Our goal is to differentiate between the scenarios in order to determine which one has the best environmental characteristics, rather than to describe the effect of a change caused by a decision. Moreover, the ReCiPe characterization method is used in this study since it is a consistent method that meets the objectives and the perimeter of impact categories that must be analyzed. ReCiPe provides a harmonized implementation of cause-effect pathways for the calculation of both midpoint and endpoint characterization factors. The ReCipe focused on: (1) providing characterization factors that are representative for the global scale and (2) aims at simplifying the complexity of hundreds of flows into a few environmental areas of interest (it covers approximately 3000 substances and has 21 impact categories).

• **Interpretation of the results**: At this point, it is necessary to consider: drawing conclusions; performing checks for completeness, sensitivity, consistency, data quality, and uncertainties; highlighting limitations, and making recommendations. During this phase, we are faced with the concept of uncertainty due to a lack of accurate data when constructing PSS scenarios. The uncertainty issues are more impactful since our approach requires a comparison between several scenarios. Thus, a sensitivity analysis becomes essential in order to determine which scenario dominates over another due to the uncertainties. In our analysis, uncertainty is related to the hypotheses considered for the Optibox Package and transport in Preventive and Curative Maintenance. For this reason, we propose to apply a simple sensitivity analysis that consists of a contribution and perturbation analysis. The goal of these analyses is to determine the effect of an arbitrary change in parameter values on the model's result. The variation of the result is calculated, and two ratios are particularly interesting to generate, such as the sensitivity coefficient (SC) and the sensitivity ratio (SR).

4 Case study in the field of heating appliances

4.1 Goal and scope study

The objective of this LCA is to carry out a comparative life cycle analysis between the traditional sales system and the new designed systems, and to develop suggestions for a better and broader use of the instrument. The context of the study is the industrial case proposed by elm. Leblanc (Bosch Group France): the analysis of a product-service system associated with the hybrid boiler, which the company already produces and offers for sale. We perform LCA analysis to examine the environmental impact at each stage of the life cycle, as well as the overall impact of each offer in particular, and to identify the categories of impact most influenced by our system, with a focus on global warming which provides data related to CO_2 emissions. Three different types of PSS scenarios based on economic models and service packages are being designed: the first one mainly provides a support on the purchase and financing phase; the second introduces the intelligent system, as it can remotely monitor different parameters by means of 18 a sensor and transmitter; and the last one, which includes upgradability service by integrating an Eco-design Balloon. The scenarios considered are listed in the table 1.

Table 1. The characteristics of PSS scenarios.

Product-Service-System scenarios			
Reference	PSS	Smart PSS	Upgradable PSS
– Basic system (10 years lifetime) – Regulatory maintenance (compulsory maintenance to ensure the proper functioning of the product system and its frequency is once a year).	– Basic system (10 years lifetime) – Transport + regulatory maintenance organization – Management and planning cost reduction in the maintenance phase	– Basic system (15 years lifetime) – Installation of OPTIBOX solution – Transport + Organization – Maintenance (regulatory, preventive and curative) – Gradually advancing in the cost reduction aspect of management & planning in the maintenance phase – Participation of ICT system	– Renewable system (20 years lifetime) – Transport + installation – Maintenance

4.2 Analysis of the results

This section outlines PSS's potential to reduce environmental impact. The PSS offers are compared at this stage of the research using environmental effect indicators that are frequently generated during the project's goal and scope phase. Table 2 shows how the environmental impact is distributed in each phase of the entire lifecycle for different PSS scenarios. The interpretation of the results led to the following conclusions.

Firstly, PSS indicates the impact was diminished by 2-3 % during the Utilization Phase due to the reduction in transportation. In the smart PSS, it is a result of reorganizing the transport services, implementing preventative maintenance, and optimizing energy use whereas, in the upgradable PSS, this is reflected by the general reduction of the system impact. Secondly, the categories with the highest impact in all PSS offers are human non-carcinogenic toxicity, terrestrial ecotoxicity, and water consumption. The human non-carcinogenic category has a high impact on the environment because it is related to the use of copper material, which has a significant percentage in the construction of the hybrid boiler, and the process associated with this effect is known as the treatment of sulfidic tailings from copper mine operations. The category of terrestrial ecotoxicity is linked to copper material manufacturing and waste plastic treatment operations. Furthermore, water consumption is affected by the use of electricity, and it is worth noting that energy consumption is the most impacting factor in the Utilization phase. Also, one of the most significant categories in our analysis is global warming (CO_2 emission) and it is worth mentioning that it is noticed environmental gains in Smart and Upgradable offers. Thirdly, in terms of an overall environmental and comparative analysis of the various scenarios evaluated, assume that Upgradable PSS has a 38% lower environmental impact than the Reference, Smart PSS at 18.6 %, and the PSS at 0.3%. In this context, and with the hypotheses considered, PSS appears as a strong environmental driver.

Table 2. The environmental impact of each life cycle phase for PSSs offers.

Scenarios	**Raw Materials**	**Assemblage**	**Installation**	**Utilization**	**End-of-life**		**Remanufacturing**
					Package	**Boiler**	
Reference	5%	5-6%	6%	> 65%	0.003%	18-18.5%	-
PSS	5%	5-6%	10%	62-63%	0.003%	18%	-
Smart PSS	7%	7.1%	7.2%	56-67%	0.003%	22.5%	-
UP PSS	1.5-3%	8.5-10%	11-12%	39-62%	0.003%	10-18%	0.001-0.15%

5 Conclusions and perspectives

The findings of this research contribute to two main aspects. First, the approach provides an easy-to-implement method to evaluate a Smart PSS offering, which put forth the environmental added-value of PSS scenarios in this case study. Secondly, the approach makes an important contribution to the existing literature by bridging the gap between traditional products and smart PSS-LCA techniques. However, there are two main limitations related to this study: one is that due to the scope of the paper, the study was carried out by adjusting to the industrial case, leaving unresolved the issue of adaptation to various PSS systems, and so failing to provide a technique with "universal" use. Secondly, another further limitation is represented by the small size of the research. In fact, many other characteristic aspects of PSS have not been investigated, such as the multiplicity of life cycles and variety of UP modes, rigorous uncertainty, and eco-concept design analysis, which can certainly represent a prospect for future research.

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