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Design for sustainability of product-service systems in the extended enterprise

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Abstract. A recent trend in modern manufacturing companies is moving from products to services. Indeed, services allow creating new business opportunities and increasing the value perceived by the customers. At the same time, sustainability is a crucial aspect for industry, which pays more and more attention to realize efficient and sustainable solutions. The research challenge is defining a structured methodology to understand how to design for sustainability considering Product Service Systems (PSS) and evaluating the effect of shifting from products to services. While product sustainability can be assessed by several tools, sustainability of PSS is almost unexplored. Furthermore, PSS requires creating an extended value creation network. This paper defines an integrated product-service lifecycle and proposes a methodology to identify a set of KPIs for both PSS and products and to compare different use scenarios. It adopts a holistic approach to assess sustainability on the basis of the three main impacts: environmental, economical and social. The methodology is illustrated by means of an industrial case study focusing on water heaters; it analyses an innovative PSS "Hot water as a Service" supported by an extended network, and compares it with the traditional scenario based on product selling supported by a vertical supply-chain. The final aim is to evaluate the service benefits and to support company decision-making.

Keywords. Design for Sustainability, Product-Service Lifecycle, Product-Service Systems (PSS), Extended Enterprise (EE), Service Engineering.

Introduction

An interesting business trend involving manufacturing enterprises is the transition from products to Product-Service Systems (PSS), which mainly consist of adding a wide range of services to increase the value perceived by the customers and better satisfy their needs over time [1]. It implies an evolution from a traditional product-oriented model to an extended product/service-oriented ecosystem. In manufacturing industry, PSS are almost realized by providing technical services that are easy to realize and can create new market potentials as well as generate higher profit margins. Furthermore, enhancing-product services (e.g. maintenance, user training, retrofitting and product monitoring, etc.) can significantly influence product performances and improve PSS sustainability. At the same time, PSS require creating new relationships between different stakeholders of the Extended Enterprise (EE) to add value with low impact thanks to the exploitation of the ecosystem capabilities.

The interrelations between products and non-physical services are complex to model and requires an integrated lifecycle considering all the activities related to both product and service. A reliable PSS sustainability assessment can be achieved only by

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considering a new integrated lifecycle and investigating the impact of each phase according to lifecycle design approaches. Such an analysis allows understanding the effective advantages in respect with traditional products to guide the evolution of the EE and support strategic decision-making.

In this context, the research aims to support the EE in PSS conception and design embracing sustainability principles. The paper proposes a methodology for holistic sustainability assessment of manufacturing products and technical PSS. The method defines the new integrated lifecycle phases and, for each of them, indicates some sustainability objectives belonging to three main factors (environment, economics and social wellbeing). Objectives can be concretized by a set of KPIs that can be measured by specific techniques (i.e. LifeCycle Assessment LCA, LifeCycle Cost Assessment LCCA, Social LifeCycle Assessment SLCA) to obtain a unique Sustainability Assessment value (SA).

The proposed method combines a set of assessing techniques and adopts them until the preliminary design stages to envisage the global impacts of different PSS design solutions on sustainability, to highlight the most critical phases and the objective in danger (economical, ecological or social), to verify the PSS benefits compared to the corresponding traditional product, and to finally support Design for Sustainability in general. The method is validated by an industrial case study focusing on hot water as a service. It analyses a new service idea where hot water service is paid as a service and heaters are no more purchased by the consumers. Analysis allows identifying the best commercial strategy for the companies involved into the EE, optimizing the design to maximize the sustainability, supporting design for sustainability decision-making, and evaluating whether and when services are more convenient than products for the global EE.

1. Research Background

1.1. Lifecycle design approaches for sustainability

Sustainability is a fundamental guiding principle for achieving highly competitive solutions and create added value. In industry, it can be achieved by adopting lifecycle design approaches that allow quantifying the sustainability of products, to identify the more advantageous trends in product innovation, and to give a tangible commercial value in terms of efficiency and costs to support customers' decision-making [2]. They consider the entire lifecycle "from cradle to grave" to estimate the impacts at each phases, from the time natural resources are extracted and processed through each subsequent stage of manufacturing, transportation, use, recycling, and ultimately, disposal. In design approaches, the designer describes a specific lifecycle scenario and determines a lifecycle strategy. Design strategies deal with the environmentally conscious selection of materials and components, the definition of end-of-life scenario and the robust analysis of consumption during use (energy, fuel, water, etc.). All relevant lifecycle phases have been designed, specified, analyzed and made available for simulation purposes. The lifecycle design approach also includes the definition of key parameters and indicators as metrics to assess the lifecycle performance (e.g. functionality, manufacturability, serviceability, environmental impact) [3].

The main scope of lifecycle approaches is avoiding potential shifting of environmental consequences from one lifecycle stage to another, from one geographic area to another, and from one environmental medium to another. Different methods have been developed for these purposes. LifeCycle Assessment (LCA) takes a holistic approach and considers the environmental impact during all phases of product lifecycle [4,5]. LifeCycle Costing (LCC) considers the total cost associated to one activity performed over one fixed time horizon by providing a global vision of cost, spread over the whole product lifetime [6]. Its application during product and system design and development is realized through the accomplishment of the LifeCycle Cost Analysis (LCCA) that is consistent with the LCA approach [7]. Recently also the social dimension has been included by the modern sustainability thinking [8]. In this direction some recent works explores the social dimension by the so-called Social LifeCycle Assessment (SLCA) [9-10].

It has been demonstrated that lifecycle approaches offer a structured methodology to proceed with comparative analysis for estimating all major impacts in the choice of alternative courses of action and not for absolute evaluation [11]. Recently, some researches coupled LCA, LCC and SLCA analysis to achieve eco-efficiency solutions [12,14]. Notwithstanding their applications generally refer to physical products, they are strongly product-centred and focus on the company perspectives. Only few examples addressed PSS assessment are presented in [15,16].

1.2. Product-service sustainability assessment

A product-service consists of a mix of tangible products and intangible services designed and combined to increase the value for customers. Value creation can be provided through an extended business network involving different stakeholders, which concur to create the services. Product-service starts from the idea of extended product [17], based on adding value by incorporating intangible services into a core product, which is the physical item traditionally offered on the market. Creating extended products implies the involvement of organizations, public bodies, tertiary service providers and customers to create a unique business framework [18], moving from a vertical supply-chain to an extended collaborative network able to support both product and service lifecycles. A PSS includes the product-service itself, the enterprise network and the infrastructures needed [19].

Services are often added to products precisely to achieve sustainability advantages of properly designed. From the economical viewpoint, services are able to create new market potentials and higher profit margins, and can contribute to higher productivity by means of reduced investment costs along the lifetime as well as reduced operating costs for the final users. From an ecological viewpoint, product-services can be more efficient thanks to a more conscious product usage, an increased resource productivity and a close loop-chain manufacturing as reported by some examples [20,15]. Finally, PSS can be also socially advanced, as services are able to support the building up and securing of knowledge intensive jobs, and can contribute to a more geographically balanced wellbeing distribution [21]. While product lifecycle modelling is a well-known technique, service lifecycle modelling is a rather new idea. It aims at representing all service data relating to its design, implementation, operation and final disposal. ISO 15704:2000 standard [22] defines the generic entity/system lifecycle phases and evolution in time. However, the biggest challenge remains performing a real and substantial assessment of sustainability for PSS and extended networks. Numerous methods to analyse service products have been recently proposed (i.e. modularization-focused, stochastic behaviour-focused, and lifecycle-focused) [23];

however some of them are very theoretical and hard to implement in practice, while others focus on the analysis of specific cases with a limited perspective [24]. None of them can provide a concrete sustainability evaluation to be applied in manufacturing EE.

In this context, lifecycle design approaches could be extended to product-service solutions and distributed enterprises. In this case, the design process chain and the product-service lifecycle converge and create interdependencies: on one hand the design choice determines the product-service lifecycle configuration as well as the EE configuration, on the other hand the product-service relations and the EE partners' characteristics affect the PSS performances and consequently the early design decision-making.

2. Integrated product-service sustainability assessment

The starting point to apply lifecycle design to PSS in EE contexts is defining an appropriate design for sustainability methodology.
The proposed method can be summarized in the following steps:

1. Definition of an integrated Product-Service Lifecycle, able to support and manage all the activities related to product design and development, service ideation and implementation, system infrastructure design and creation, product-service delivery, until PSS disposal. Lifecycle modelling considers the product as well as the technological infrastructure and the services;
2. Identification of the sustainability objectives for each lifecycle phase. Three main aspects have been considered: environment, economics and social wellbeing;
3. Definition of the relevant lifecycle phases and, for each of them, of a set of KPIs. About sustainability, the relevant impacts arise from the end of the design stages until the system end-of-life;
4. Definition of reliable measuring techniques to assess the relevant KPIs. According to lifecycle design, LCA, LCCA and SLCA are chosen: LCA focuses on the impact on environmental resources and ecosystem, LCCA estimates the total costs by considering the companies involved, the consumers and the dismissing consortiums, and SLCA estimates the impact on human resources and human health;
5. Measurement of the sustainability impacts by applying the selected techniques. Impacts are separately measured for each relevant stage and any design solution as well as EE scenario. The scenario depends on the companies involved into the EE, the user typologies, profiles and behaviours, as well as the considered lifetime to carry out targeted analyses. The KPIs measurement allows quantifying the achievement of the defined objectives;
6. Calculation of the global sustainability assessment of product-services by combining the selected techniques and normalizing the single indexes to have a sustainability global assessment (SA), as expressed by Eq. (1):

$$LCA + LCCA + SLCA = SA \quad (1)$$

The proposed methodology is schematized in Fig.1. Sustainability assessment focuses on the operative phases; indeed, the impacts of ideation and design stages is limited and they are almost similar for different solutions, so their contributions can be neglected as far as sustainability investigation is concerned.

Thanks to its pragmatic procedure, the method is general and can be straightforwardly carried out for assessing PSS as well as traditional products: for the latter, the lifecycle will be simplified by considering only the product-oriented activities, but the method doesn't change. Such method extends some recent works focused on product-services assessment [15,16]. It aims to define a structured methodology to benchmark different design solutions by a sustainability viewpoint as already known in product design for other specific purposes, for instance collaboration [25]. Such a method has three main advantages: it well addresses product-services as it exploits lifecycle approach and it can be adopted until the preliminary design stage to support top managers' decisions, to objectively compare the impact of different solutions and to validate the technicians' choices. Moreover it can be easily applied to both products and PPS to compare design alternatives and alternative scenarios, evaluating the consumed resources and choosing the less-impact one.

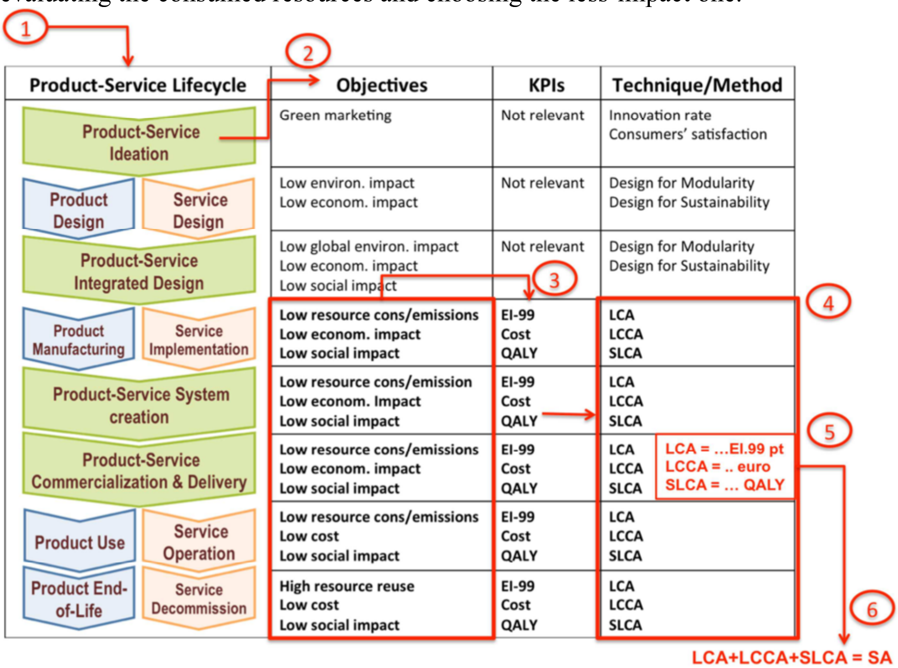

Figure 1. Methodology for Product-Service sustainability assessment

2.1. *Lifecycle sustainability impacts*

The lifecycle analysis considers all significant data referring to the analysed phases for product (manufacturing, use, end-of-life), service (implementation, operation, decommission) and product-service system (creation, commercialization and delivery). For each phase, three impacts are separately estimated. Environmental impact is measured by Eco-Indicator99 (EI-99), considering Ecosystem Quality impact and Resources consumption. The unit of measurement is EI-99 point (Pt). Economical impact considers the lifecycle costs in terms of resources consumption (MegaJoule) as well as material use and transformation (MegaJoule or euro/dollars), from product manufacturing to service implementation phases by considering all the companies involved in the EE, until the end-of-life and decommission in charge of the dismissing consortium and involved entities. It adopts the Equivalent Annual Cash Flow technique (EA) to transform a generic cash flow distribution into an equivalent annual distribution by cost actualization according to Eq. (2):

$$EA = P\frac{(i+1)^n * i}{(i+1)^n - 1} \quad (2)$$

where *n* is the lifetime years' number, *i* is the generic discount rate (for example 3%), and *P* is the value during the entire lifetime. The impact is expressed in Euro. Finally, social impact considers separately Human Health contributions according to EI-99 methodology as before. Impact is expressed into QALYs (Quality Adjusted Life Years). Such values can be calculated by LCA and LCCA software tools (i.e. SimaPro, Gabi, Relex).

2.2. Normalization procedure

The results calculated by means of LCA, LCCA and SLCA are coupled to obtain a unique sustainability index via proper data normalization. Starting from different units of measurement (i.e. EI-99 Pt, euro, QALYs), environmental and social impacts are "monetized" to obtain a final monetary (expressed in euro). Then, the three monetary values can be summed to assess the overall sustainability. Higher is the impact, and lower is the sustainability. Normalization is achieved by the following equations, which are based European average data for having a consistent redefinition.

The environmental impact originally expressed in EI-99 pt. can be translated into PDFm^2yr (Potentially Disappeared Fraction of species per square meter per year) and MJ (MegaJoule), and normalized by Eq. (3) and Eq. (4):

$$Pt = PDFm^2yr \text{ and } (PDFm^2yr) * 1{,}4 = euro \quad (3)$$

$$Pt = MJ \text{ and } MJ * \frac{0{,}00411}{lifetime} = euro \quad (4)$$

The social impact, that originally expressed in QALYs, can be multiplied for the estimate cost for year according to recent European data, be Eq. (5):

$$1\ QALYs * 74.000 = euro \quad (5)$$

3. The industrial case study

3.1. Hot water as a service

The case study has been realized in collaboration with an Italian company producing heating and hot water systems, which is a world leader in this field. The company is actually organized in a vertical supply-chain and adopts a product-oriented development process. Collaboration with partners and suppliers is limited to design innovation and cost reduction.

The case study focuses on a new PSS idea consisting of selling hot water as a service instead of heater products (i.e. condensing boilers). The idea starts from the high inefficiency of actual product solutions, due to wrong assistance actions during the product lifetime, which consequently led to a significant increase of energy consumptions, costs and environmental impact. In case of traditional product, customers usually purchase the heater from a dealer (at the final price of about 2.000,00 euro), a technician installed the product at home and a third company cares about maintenance annually (costing about 100 euro/year). Otherwise, the PSS solution consists of providing the heater for free and guaranteeing the hot water service by remotely monitoring the product, verifying its performances, and caring about its functioning also by predictive maintenance. The consumer will pay a unique monthly fee (i.e. 36 euro/month). The lead company will remain the product owner and it will plan specific interventions or product substitution when necessary (for instance, every 5 years). Affiliated partners will provide product monitoring and maintenance actions. After a certain lifetime, the consumer can choose if renewing the service contract or buying back the product at a special price. The considered lifetime is 15 years. PSS scenario implies a strong collaboration between the lead company and the technical assistance centres, as well as the third parties caring about maintenance and about renewing or dismantling. Fig.2 shows the conceptual PSS framework and highlights the novelties in respect with the traditional product one.

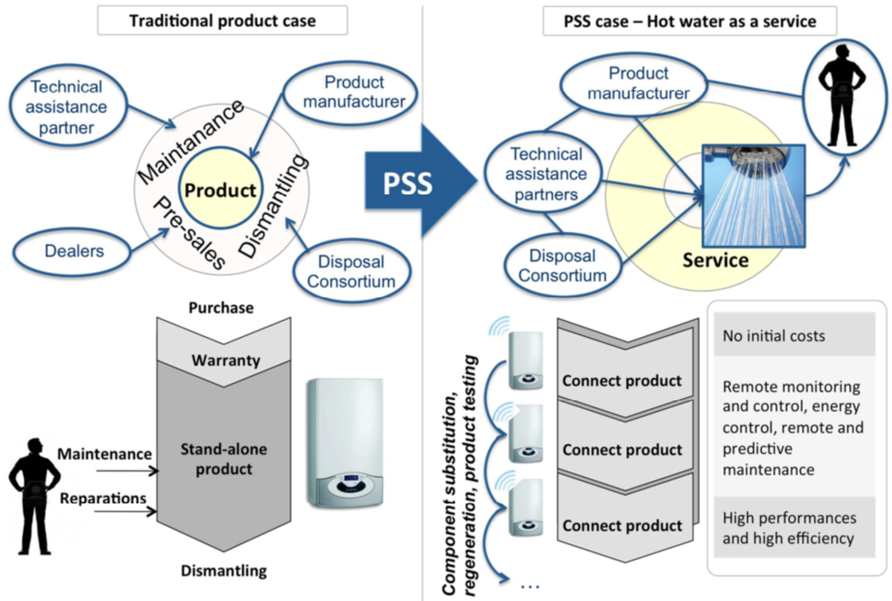

Figure 2. The case study framework: PSS and traditional product comparison

The research questions are: which is the global impact on sustainability of the new PSS solution? Which is the more sustainable model to sell the new PSS (years of product substitution, price for buy-back, price for monthly fee)? What are the achievable benefits in respect with the traditional product? Such questions are investigated for four different use scenarios, differing in electrical and thermal energy efficiency: 1) existing apartment, 2) new apartment, 3) existing detached house, 4) new detached house.

3.2. PSS sustainability assessment and comparison with traditional product

The sustainability assessment is achieved by applying the proposed method to PSS lifecycle stages as reported in Fig.1. For the product manufacturing phase, LCA considers the environmental impact produced by all the components used for the production and the final assembly, and data are organized according to the main functional entities (e.g. pressure vessel, heat exchanger, burner, embedded electronics, external case, interface, etc.). A 5% cut-off is applied to not consider those parts that have a limited impact. LCCA considers the global manufacturing costs (about 600 euro/product). SLCA considers the human health impact similarly to LCA. For the service implementation phase, LCA and SLCA consider the impacts of all the items necessary to create the service infrastructure and the service operational aspects (e.g. central gateway, connection board, Zigbee module, electronics for control units, etc.). LCCA considers their costs. For product-service system creation, analyses consider the impacts and costs of the additional components and the system infrastructure that must be added to the traditional stand-alone product (e.g. call-centre, the personnel employed there, the wiring network). Product-service system commercialization and delivery comprehend the transportation impacts and costs as well as the point of sales impacts. The analysis of the product use and service operation phases consider the habits of the consumers in the four use scenarios, according the European average data, over the considered lifetime (1-15 years). For LCA both electric and gas thermal energy consumptions are considers. While for traditional product there is a decrease of performance with the passage of time as suggested by real data monitoring, PSS performance have higher and constant performances due to a continuous control of the machine status, real-time monitoring, predictive maintenance and constant assistance (i.e. PSS machine is monitored and parts can be substituted in advance to guarantee a high quality performance for the whole lifetime). LCCA considers the costs generated by the resource consumptions (i.e. electric energy at about 0,2 euro/kWh, thermal gas energy at about 0,08 euro/kWh). The product-service end-of-life considers the impacts and the costs for product regeneration or substitution as well as service decommission. The present PSS case considers 5-year regeneration: impacts are optimized as they are directly managed by the EE, who cares about all phases (i.e. product regeneration, component substitution and reuse, service updating, service decommission).

The following tables summarize the main research results. Tab.1 shows the obtained results for the PSS case for 15-year lifetime. It investigates a specific use scenario (i.e. new apartment) and shows the separated analysis values for LCA, LCCA and SLCA, and the global Sustainability Assessment (SA). In this way the impact of each phases of the integrated product-service lifecycle is expressed in terms of three categories (environment, economics, social wellbeing). Tab. 2 compares PSS impacts for different scenarios: it contains the global SA results obtained by summing the three contributions after normalization. Tab. 3 compares the PSS case and the traditional product case by considering different lifetimes for two different scenarios (i.e. new home and existing home). It is worth to notice that PSS is more convenient for both scenarios, regardless the user habits. Furthermore, it is evident how new buildings allow maximizing the PSS sustainability. Data con be investigated also over the years to better highlight the PSS advantages in relation to traditional product and to understand how benefits evolve along the lifetime.

Table 1. Lifecycle analysis results for PSS (LCA + LCCA + SLCA)

PSS CASE – New apartments (15-years lifetime)			
Lifecycle phases	**LCA (Pt)**	**LCCA (€)**	**SLCA (QALY)**
PRODUCT manufacturing	1099,67	€ 1.800	9,18 E-03
SERVICE implementation	1986,84	€ 1.500	
PRODUCT-SERVICE SYSTEM creation	51,42	€ 250	
PRODUCT-SERVICE Comm. & Delivery	1,01	€ 15	
PRODUCT-SERVICE SYSTEM use/operation	675,33	€ 6.541,84	5,87 E-03
PRODUCT-SERVICE SYSTEM EoL/decommission	-2687,74	-€ 1.650	-4,79 E-03

Table 2. Sustainability assessment for different scenarios

PSS - SUSTAINABILITY ASSESSMENT (SA)				
15-years lifetime	**Existing apartment**	**New apartment**	**Existing detached house**	**New detached house**
Env. Impact (norm.)	€ 107,42	€ 153,26	€ 104,83	€ 135,46
Eco. Impact (€)	€ 9.941,76	€ 36.573,76	€ 8.441,84	€ 26.233,20
Soc. Impact (norm.)	€ 838,01	€ 2.250,42	€ 758,46	€ 1.702,02
GLOBAL SA (€)	€ 10.887,19	€ 38.977,44	€ 9.305,13	€ 28.070,68

Table 3. Comparative sustainability assessment for PSS and traditional product

	PSS		**Traditional product**	
Lifetime	**New detached house**	**Existing detached house**	**New detached house**	**Existing detached house**
15	€ 10.887,19	€ 38.977,44	€ 11.719,33	€ 41.341,75
10	€ 7.147,98	€ 25.189,29	€ 7.971,47	€ 27.484,29
5	€ 3.653,52	€ 12.469,84	€ 4.177,07	€ 13.402,05

The proposed analysis can be repeated for other use scenarios to simulate different service features (e.g. monthly rate, bay-back period, product substitution period, etc.) and finally understand when the product-service solution is particularly advantageous. Furthermore, it allows easily comparing PSS solutions with traditional product solutions on the basis of both single impacts and global sustainability.

The methodology application to an industrial case study verifies the fulfillment of the following purposes: 1) identification of more sustainable strategy for a specific PSS and EE made up of the lead company, several partners, the dismantling consortium and the consumer; 2) easy comparison between different design solutions in order to identify the more sustainable one; 3) support to design for sustainability decision-making; 4) identification of those conditions when services are more convenient than products by considering the impacts of the entire EE.

4. Conclusions

The paper proposes a methodology to support design decision-making for PSS by assessing the global sustainability. It allows a deep sustainability investigation by highlighting the impacts for the different phases of an integrated lifecycle with respect to three categories: environment, economics and social wellbeing. Its validity is demonstrated by an industrial case study proposing a new service idea (hot water as a service): it compares different PSS scenarios and highlights the benefits in respect with the traditional product one. Future works will focus on method applications to different industrial scenarios and its validation and optimization also by effective performance evaluation and feedback.

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