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A LIFECYCLE DESIGN APPROACH TO ANALYZE THE ECO-SUSTAINABILITY OF INDUSTRIAL PRODUCTS AND PRODUCT-SERVICE SYSTEMS

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Keywords: eco-sustainability, lifecycle design, product-service system, industrial product

1. Introduction

Lifecycle design approaches are widely used in industry to quantify the eco-sustainability of products and to give them a tangible commercial value in terms of efficiency and costs. They are commonly applied for two reasons: to identify the more advantageous trends in product innovation and to support customer's decision-making. Recently, increasing competition and technological developments result in high time, cost and development pressure. These facts induce the need for differentiation for most companies but also for reducing time-to-market. In this context, companies are pushed to move from a product-centred perspective to a product-service one, towards the new concept of "extended products". This consists of adding a wide range of services connected with the product use in order to increase the value perceived by the market. Extended products can also be personalized by diversification of services, which is rather easy to realize and relatively inexpensive as it no longer focuses on the product features but on a wider choice of product-related services: the product is still the same but the service offer changes. In this way, companies can add a full service portfolio to their products or even sell only the supporting services. The foremost example is probably represented by the case of coffee machines: a producer had the idea of only selling the coffee pods, giving the machine for free. It was a revolution: after some years there are still only two producers who exist in the market. In this context, companies are required to change their business models to no longer offer products but flexible product-service systems. However the main question is: how can the performance offered by the new service-based assets be estimated and quantified? Whereas products can be validly estimated by lifecycle design assessment methods, no structured and certified method has been defined for service estimation yet. Contrariwise, both the industry and market need such tools to guide their choices.
The present paper uses the lifecycle design approach to understand the eco-sustainability of product-service systems and compares them with traditional industrial products. Such a tool allows environmental and economical performances to be easily estimated and products and product-services systems to be compared by objective lifecycle parameters. It can be validly adopted by engineers, top managers and customers: engineers have useful data to better understand the value of the product-service solutions and to compare them with traditional products; top managers have performance indicators to support the strategic decision-making; customers have tangible data to compare product-based and service-based solutions and to support their purchasing decisions.
The proposed method follows the LCA approach and exploits LCA and LCC indicators to estimate and compare eco-sustainability and feasibility for product and product-service solutions. It considers the whole lifecycle phases (manufacturing, use and end-of-life) and finally measures the achieved performance in terms of environmental and economic impact. The method has been applied to an industrial case study focusing on a washing machine product and service. In particular, it aims to

compare two scenarios: product and product-service scenario. The former analyses the traditional use of a washing machine, the latter focuses on an innovative business idea consisting of buying only the washing cycles actually needed, having the machine for free. Experimental data have been calculated by considering an effective use case.
The paper is structured as follows: Section 2 introduces the research background considering the existing lifecycle design methodologies and presents the transition model from product to product-service scenario. Section 3 describes the main features of the lifecycle eco-sustainability for products and product-service systems and the relative metrics. Section 4 presents the case study and analyses the results obtained by comparing a product and a product-service system. Section 5 contains conclusions and future works.

2. Research background

In recent years, in the market context there has been a move by consumers towards extended products and services. Due to this aspect, innovative design approaches have changed methods to conceive, analyse and develop industrial products in industrial departments. The first change, in enterprises, concerns the transition from the product equipment to product-service provision. This means that the new industrial perspectives are oriented not only to the realization of products but also to their entire lifecycle considering after-sale assistance. This is the second great change of the modern engineering scenario finalized to take into account the whole lifecycle of products and services. For these reasons important issues are analysed in the design process in order to improve product performance, reduce the costs in use and the environmental load.

2.1 Lifecycle engineering

Lifecycle engineering regards designing the product lifecycle through choices about product conception, structure and materials in the early design phase. In a lifecycle engineering approach, these considerations are integrated in order to achieve an optimal product specification which takes into account all phases of the product lifecycle. Jeswiet defines lifecycle engineering as: "*engineering activities which include: the application of technological and scientific principles to the design and manufacture of products, with the goal of protecting the environment and conserving resources, while encouraging economic progress, keeping in mind the need for sustainability, and at the same time optimizing the product lifecycle and minimizing pollution and waste*" [Jeswiet 2003].
The design process chain and the product/service lifecycle are two different points of view which converge on the same feature. In particular, the two chains are interdependent; for this reason the design choice determines the product/service lifecycle configuration, in the same way that the different lifecycle alternative gives suggestions for the optimal design solution. All product development phases are influenced by the requirements from any lifecycle phases [Melk 2007]. At a conceptual level, in the design approach, the designer describe a specific lifecycle scenario and determines, first of all, a lifecycle strategy. Design strategies reporting to the pre-production/manufacturing phase 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 product lifecycle phases have been designed, specified, analyzed and made available for simulation purposes. The lifecycle design method includes the identification and the definition of key parameters and indicators which include functional performance, manufacturability, serviceability, and environmental impact. These lifecycle parameters are used as metrics to assess the lifecycle performance (such as environmental, economic and social) and to compare and analyse alternative solutions.
Life Cycle Assessment (LCA) indicators and methods, for example, have been developed to identify and avoid potential shifting of environmental consequences from one lifecycle stage to another, from one geographic area to another, and from one environmental medium to another. That is, LCA takes a holistic approach and therefore presents a more accurate picture of the true environmental trade-offs of engineered products, services or human activities. LCA covers all phases of product lifecycle "from cradle to grave"; this means that it starts from the extraction of raw materials from the Earth to the production and distribution of energy through the use, reuse and final disposal of a product. LCA and

its relative tool are intended for comparison and not absolute evaluation, thereby helping decision makers to compare all major environmental impacts in the choice of alternative courses of action [Curran 1996]. The method was standardized by ISO in 1997 and updated in 2006 [ISO 14040, 14044 2006].

Life Cycle Costing (LCC) can be defined as the total cost associated to one activity performed over one fixed time horizon [Woodward 1997]. The Life Cycle Costing (LCC) cannot be considered only the market value of product, but a global vision of cost, spread over the whole product lifetime. The LCC method is consistent with the LCA approach described above [Nakamura 2006]. The application of LCC methods during product and system design and development is realized through the accomplishment of lifecycle cost analysis (LCCA). This approach may be defined as a systematic analytical process of evaluating various designs or alternative courses of action with the objective of choosing the best way to employ few resources.

2.2 Product and product-service transition

Increasing competition and technological development result in high time, cost and development pressure. These trends induce the need for differentiation for most companies but also for reducing time-to-market. This fact encourages a move from a product-centred perspective to a product-service one for two main reasons. Customers are looking for solutions and benefits (not for products), or even better they want intangible things (such as fun, success, fame, vanity etc.). Diversification of services can be low-cost and quick to realize, as it no longer focuses on the product but on a wider choice of product-related services offered. Thoben et al. [Thoben 2001] described the concept of the extended product, a means of adding value by incorporating services into a core product. They argued that increasing value in this manner is necessary to compete in dynamic, global markets where customers have access to products from all over the world. Figure 1 schematizes the shift from the product to the new product-service perspective. It also delivers an appropriate model to link products, product related services and the needs of the users. Two main scenarios can be distinguished: Product+Service and Product2Service.

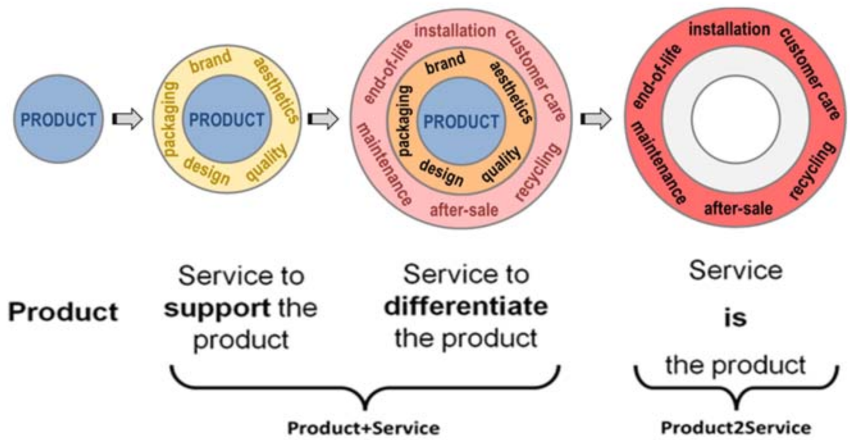

Figure 1. The concept of Extended Products and the two service-oriented scenarios: Product+Service and Product2Service [Thoben 2001]

The traditional view is represented by the Product as the physical item offered on the market. The Product Shell describes the tangible “packaging” of the product (e.g. a car including equipment) and a set of Supporting Services as intangible additions, which facilitate or support the use of the product (e.g. maintenance plans or mobility guarantees). This shell represents the Service to support the product. Differentiating the services offered allows the Extended Product to be positioned differently on the market (e.g. coding of personalized functionalities). At this point, two scenarios can be realized depending on the position of the producer company. The Product+Service scenario describes the simultaneous offering of the tangible product (Core Product and Shell) extended with proper tailored services. In this case, both physical products and services contribute to the company revenues, their balance needs to be adaptively determined and continuous innovation of services assumes a key competitive advantage (e.g. a car and the associated financial, maintenance and configuration services etc.). Contrariwise, the Product2Service scenario is sharply decoupling the manufacturing of goods and selling of services, where in most cases the physical goods remain the property of the manufacturer and are considered as an investment, while revenues only come from the services (e.g. by selling "mobility" instead of the physical car). The first sees services as a means of creating a competitive advantage by adding value in the customer's view and making products more difficult to imitate, creating a "win-win situation" [Davis 2005]. The second sees services as potentially replacing products and is concerned with environmental, rather than financial motivation.

In this context, companies are currently moving from traditional product-centred design to product-service design in order to provide services according to the new approach described-above. However, companies can have difficulty in evaluating which the real differences for industrial practice are. Indeed, the extension of products in terms of Product+Service and Product2Service will constitute physical products as well as the associated accessories or services. Furthermore, the design process will not only conceive the product but also the Services and will be realized in a wider and more complex manufacturing system. Thus, depending on the type and core competencies required to supply the associated services, there may be several business partners collaborating very closely towards the common goal of making the sale of the package attractive. Working together in design and production networks results in an extension of the traditional company model and the creation of an industrial model for collaboration (e.g. Virtual Organizations, Virtual Enterprise) [Byrne 1993]. At the same time, also the enterprise model will change by moving from a traditional single enterprise producing products to a virtual enterprise providing services around the product as a temporal association of several companies (figure 2). Compared with traditional manufacturing enterprises, where the ecosystem is represented only by the producer, the new virtual enterprise service-oriented involves customers as a part of the enterprise and several companies participating in the service offer, who usually only have a small participation in this virtual enterprise as they are part of a numerous ecosystem.

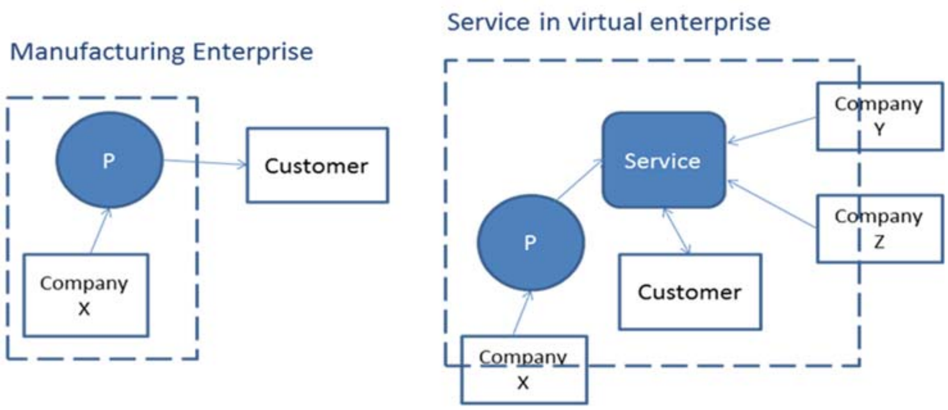

Figure 2. Comparison of business models adopted by manufacturing enterprises and service-based enterprises

3. Product and product-service design oriented to lifecycle and eco-sustainability

There are different drivers which consumers can consider in their marketing choices. Brand, cost, aesthetics and performance are the most common decision-making drivers, but in any case they are not completely exhaustive or detailed for consumers. New specific items, linked to the whole product lifecycle, should be given to consumers for their choices. This is the case, for example, of lifecycle parameters, which are also used by designers when conceiving and developing new products or product-services.

The proposed approach aims to support designers in the main design and evaluation activities to define new products and the relative product-service systems by considering the eco-sustainability along the whole product/system lifecycle. It consists of applying a well-known technique such as the lifecycle design approach (as reported in section 2) for an innovative purpose: not simply to assess the product impact but also to evaluate both products and services in the new service-oriented scenario. As a consequence, it can help designers to conceive successful product solutions in the early design stage, but it also becomes a new challenge to supply additional services. It offers also the possibility of customizing the product or replacing it with the relative service by comparing the results. In this new market scenario, engineers and designers can use the lifecycle principles and guidelines to understand and evaluate the feasibility and the eco-sustainability of the new product-service system. Figure 3 shows the four main design phases in the case of product and product-service design and the methods and tool utilized at each step. The transition from product to product-service system has a great impact, especially in the conceptual design phase and in the embodiment design phase. It is possible to clearly define the new perspective and the new tools utilized in these two phases of product-service development.

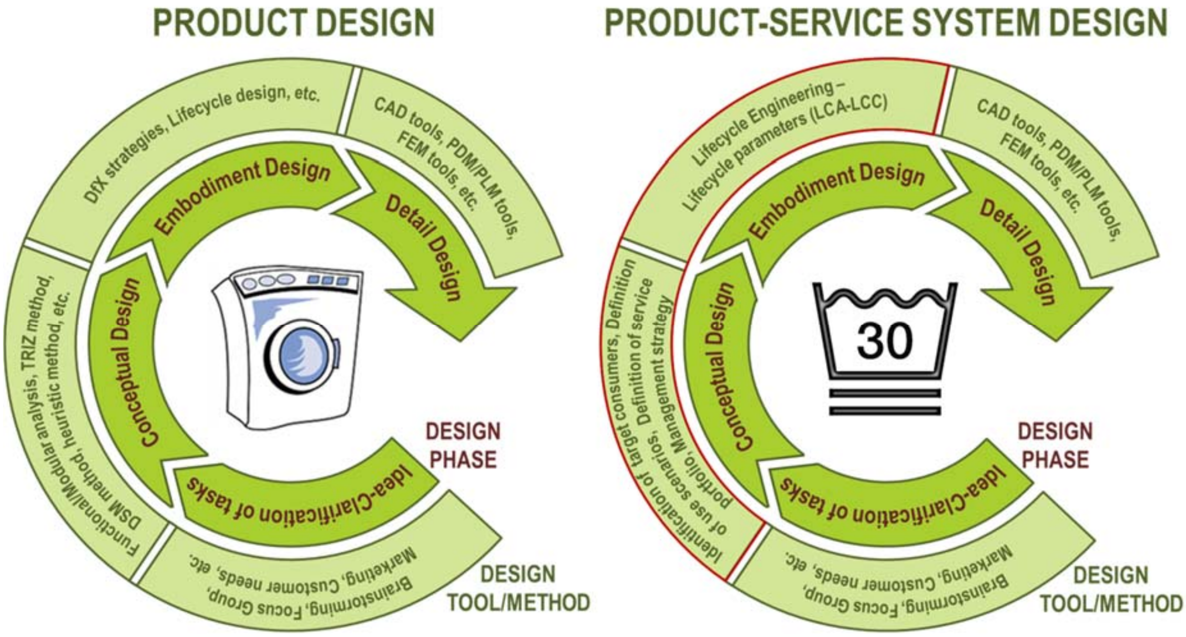

Figure 3. tools and methods used in the development of design phases for product and product-service system design

The first design step is the same for both product and product-service systems designs and is based on tools which help in generating and stimulating new engineering *Ideas* and the possibility to *Clarify the product/service tasks*. Together with Marketing expertise, designers use specific tools for this phase, such as focus groups, questionnaires, collection of customers' needs, brainstorming, etc. Differences in the two cases focus on how consumers' needs are satisfied and how the enterprises can make profits.

The second design step, called *Conceptual design*, is focused on the customer satisfaction by the implementation/realization of the original idea. The principal aspects to be considered are:

- Identification of target consumers and classification on the basis of their habits.
- Definition of use scenarios for the different family of consumers previous identified.
- Definition of service portfolio to provide to consumers.
- Definition of Management strategy for the product-service and its implementation

The last point of this analysis is strongly oriented to the service lifecycle, particularly the way the services are managed during the use and end-of-life phases. A management infrastructure must be considered in this step for a complete conceptual analysis of the product-service system.

The third step is the *Embodiment design*, where the product-service is developed in accordance with technical and economic criteria. In this step the tools and strategies evolve from a specific target to

maximize, for example assemblability, disassemblability, reduction of costs, (DfX) to the entire aspects of lifecycle (lifecycle design). For the product-service system, in fact, it is necessary to analyse the whole lifecycle in the embodiment design phase in order to verify the feasibility and the eco-sustainability of the proposed product-service. Furthermore, the calculation of explicit lifecycle parameters permits the economic and environmental sustainability to be numerically assessed and different alternatives or the benefits to be compared to the realization of product.
For the above mentioned reasons, lifecycle engineering is a suitable way to conceive, design and develop new product-services in the modern business scenario. The parameters introduced by this approach are becoming very widespread in industrial departments and they are useful not only in the embodiment design phase but also for the alternatives comparison and decision-making tool in detailed design phase. In this work two parameters are proposed (LCA and LCC) which evaluate both the environmental and economical sustainability for the product/product-service lifecycle. The use of few, simple and easily parameters makes the lifecycle approach the best way to compare the eco-sustainability of product versus product-service. In the global context lifecycle metrics seriously lack tools which are able to collect information regarding product structure and models easily and automatically so as to give designers the required parameters. Furthermore, a sensitive analysis is necessary for the evaluation of different scenarios of use, particularly in the case of product-service. The customization of services on consumers' needs requires a specific analysis of use scenario in order to have a clear value of lifecycle parameters. For these reasons the lifecycle approach is a new challenge in the industrial firms, but requires some improvements to save time and reduce complexity.
The last step is the *Detail design* step in which the use of computer-aided tool allows the design concept to be transformed into a virtual model for the manufacturing and production.

3.1 LCA approach and parameters

LCA is the most objective tool available for generating the environmental profile of a product or service and it allows different alternatives to be compared from the point of view of environmental sustainability. LCA addresses the environmental impact from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal. The LCA method comprises 4 distinct phases:

- the goal and scope definition
- inventory analysis (LCI - Life Cycle Inventory)
- impact assessment
- interpretation [ISO 14040, 14044 2006]

LCA, however, requires detailed product design information which makes it unsuitable for use in the early design process stages when detailed specifications are not available [Sakao 2007], [Reap 2008]. Also, LCA could be very costly and time consuming so only large companies can afford to do it. To overcome these obstacles new simplified methods have been developed in recent years (S-LCA – Simplified Life Cycle Assessment) which permit an increase in LCA usability in the early design stages (embodiment design). S-LCA adopts dedicated tools to estimate the environmental impact of product alternatives and to predict environmental costs or burdens for manufacturers [Kaebernick 2003]. The LCA value calculation is performed in compliance with existing regulations. One of the most famous evaluation methods, called Eco-indicator (EI-99), permits a normalized and weighted value of environmental impact in three major categories of environmental damage to be obtained:

- Resources.
- Ecosystem quality.
- Human health.

The EI-99 parameter have been proved to be meaningful metrics for designers to aggregate LCA results into easily understandable and user-friendly numbers or units [Goedkoop 2000].

3.2 LCC approach and parameters

The principle of LCC calculations is the same as the Net Present Value (NPV) calculation, which consists of discounting cash flows over the time horizon of one investment. While NPV is typically

used as a decision making tool for strategic decisions and business planning, LCC techniques normally aim to take into account a wide range of technical data which can occur during the whole product lifecycle, in particular, energy or fuel consumption in use, maintenance operations, end-of-life scenarios, etc. [Molinari and Tosatti 2006]. For these reasons, the main application of LCC for a given product, system, or structure is traceable to decisions made during conceptual and preliminary design. These decisions pertain to operational requirements, performance and effectiveness factors, design configuration, maintenance concept, production quantity, utilization factors, logistic support, and disposal. LCC is a parameter to understand the effective cost of a product/service in its whole lifecycle.
For the calculation of costs in different time periods, two formulas (1, 2) are used:

- Financial formula for capitalization (consider the increasing of costs). P_n is the Unitarian capitalization value considering the specific consumption.

$$P_n = P_{n-1} * (1 + i_c) \tag{1}$$

- Financial formula for actualization of costs.

$$LCC = \frac{P_n}{(1+i)^n} \tag{2}$$

The items in the formulas are:

- n = year
- i_c = specific discount rate calculated for different consumptions.
- i = generic discount rate (for example i = 3 %)

The LCC value can be useful not only for designers in the product design, but also for consumers as a decision-making parameter. Therefore, it is important to assess the relationship between LCA and LCC during product/service lifecycle to quantify the eco-sustainability. In this way the added value of the product/service strongly increases the consumers' appeal.

4. Case study analysis in household appliances market

The proposed case study is represented by an innovative idea in the household appliances context, in particular in the field of washing machines. The traditional product offer is based on selling the "washing machine"; the new product-service system is represented by selling "washing cycles", getting the machine as a loan for use. The latter is clearly a Product2Service solution. The proposed lifecycle approach is applied for the case study analysis and important results can be retrieved from the analysis of lifecycle parameters, as the possibility to compare the economic and environmental sustainability of product or the alternative product-service.

4.1 Selling washing machines versus selling washing cycles

The analysis of lifecycle parameters permits the eco-sustainability of selling/buying the product "washing machine" or the alternative product-service system "washing cycle" related to the product to be established (figure 4). The difference between selling and buying depends on the company's or customer's perspectives. The overall results have been obtained by analyzing the whole product lifecycle phases: manufacturing, use and end-of-life.
The awareness of product "washing machine" is well-known both for consumers and designers. The product-service "washing cycle" is an example of a product2service system in which the consumers only buy the service related to the industrial product whenever they want it. Different kinds of design methods can be adopted for the development and the management of product-service. LCA and LCC are suitable indices to evaluate the feasibility, environmental and economical sustainability of product-service. The maximum load capacity for the analysed "washing machine" similarly to a "washing cycle" is 7 kg. The same washing machine is considered as data input for the analysis (LCI). In this

work transport in the various steps of product lifecycle have not been considered because the transport vehicles and distances are the same for both the product and product-service system.

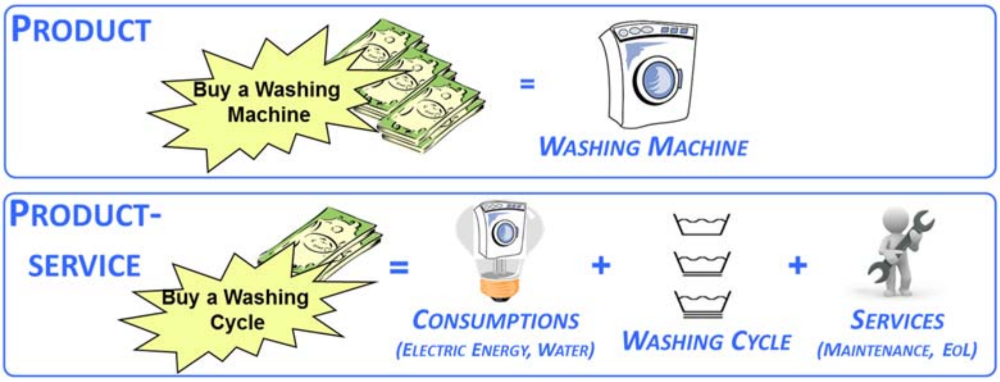

Figure 4. "washing machine" product and "washing cycle" product-service: analysis of differences in the proposed case study

4.2 Washing machine and washing cycle manufacturing phase

The manufacturing phase of "washing machine" product considers all the components used for the production and the final assembly. The product BOM (Bill of Material) and product structure are the starting point of the lifecycle analysis in this specific phase. Due to the high numbers of components used to produce a washing machine, the small parts which have a weight value less than 5% of the total weight of the washing machine are considered cut-offs. The manufacturing and assembly phases are defined as the starting point of the total lifecycle (t_o). Each environmental impact and cost is calculated starting from this time.
As far as the manufacturing phase of "washing cycle" product-service is concerned, the same manufacturing and assembly process as the "washing machine" product are considered, plus other components necessary, for example the payment of washing cycle (money box), communicating energy consumption (energy-meter system), after sales assistance (remote maintenance system), etc. All these other components are necessary for the infrastructure system of the service system management.

4.3 Washing machine and washing cycle use phase

The lifetime period considered for the product "washing machine" is 6 years and the data considered in the whole lifecycle analysis are: electric energy consumption (6718 MJ), water consumption (103.500 l), detergent consumption (186 kg) and components necessary for maintenance (ENEA report). During the product lifetime, in fact as for other products, some components may need to be replaced as a result of their failure or breakage. The components which have to be replaced considering both their lifetime and the product lifetime are: the hydraulic pump, electrical resistance, door seal, elastic belt, pressure valve, drain pipe group. The proposed data is estimated as an average value of consumptions (energy, water, detergent) for the different types of washing cycles for the same family of washing machines (7 kg load capacity). For the LCC analysis the specific discount rate for the consumptions is: $i_{electric\_energy}$ = 3,73 %, $i_{domestic\_water}$ = 3,78 %, $i_{detergent}$ = 3,14 %.
For the product-service "washing cycle" the same lifetime period (6 years) is considered. The use scenario, on the other hand, considers only a specific washing cycle of coloured clothes or underwear at low temperatures (30 °C) with the specific value of consumptions (energy, water, detergent). For example, a typical value of consumptions for this washing cycle are: electric energy consumption (4,28 MJ), water consumption (53 l), detergent consumption (0,03 kg). This means that the evaluation of lifecycle parameters is more accurate in this second case, based on the specific habits of consumers. However, this is one of the whole possible scenarios of use and limits the analysis in this specific context. Different use scenarios should be analysed and provided to consumers in order to have a large

number of alternatives for the comparison of eco-sustainability with the product "washing machine". Lifetime maintenance is also considered for the product-service system.

4.4 Washing machine and washing cycle end of life phase

For the end-of-life treatments of the product “washing machine” a certain percentage of the total product mass/weight is considered. In this specific case, in accordance with European Directive on Electric Equipment Waste (WEEE) the following are considered: recycling (55 %), reuse (5 %) remanufacturing (5 %) and disposal (35 %). This general data can be used for the washing machine product which requires an accurate sensitive analysis based on different percentages of end-of-life treatments. For the product-service system “washing cycle” the end-of-life treatments are managed by the same firms which provide the product-service. For this reason, a certified inverse supply-chain for end-of-life treatments are possible in this case. The LCA and LCC results for end-of-life are more accurate referred to the washing machine product analysis and do not require the sensitive analysis. Table 1 shows a summary overview of the end-of-life treatments for the components in the case of product-service system.

Table 1. End-of-life treatment overview in the case of product-service system

Components	EOL treatment	Components	EOL treatment
Aluminium alloys	Recycled	Steel and iron	Recycled
Plastics	Recycled	Electronic components	Different treatment
Rubber	Recycled	Small parts (screws, rivets, etc.)	Disposal

4.5 Results and discussion

This preliminary analysis demonstrates how the transition from the perspective of product to product-service system design gives important benefits in terms of environmental and economical sustainability in the whole lifecycle. These benefits are highlighted by the analysis of the lifecycle parameters which can be used as a market strategy for the industrial firms as a new methods to design and develop new product/service. For the proposed case study the general results are shown in table 2.

Table 2. Lifecycle value for the eco-sustainability comparison of product “washing machine” and product-service system “washing cycle” in a described configuration

Lifecycle parameters	Product (Washing Machine)			Product-service (Washing Cycle)		
	Manuf.	Use	EoL	Manuf.	Use	EoL
Environmental (LCA) [EI99 Pt]						
• *Human health*	6,65	30,85	–2,95	6,84	22,81	–3,42
• *Ecosystem quality*	2,71	6,04	1,52	2,73	5,15	0,48
• *Resources*	9,05	76,00	–2,66	9,76	71,84	–5,18
Total	127,21			111,01		
Economic (LCC) [€]						
• *LCC value*	88,22	1282,51	24,87	96,36	1222,97	–48,11
Total	1395,60			1271,22		

It is clear that in the proposed analysis for the product-service system (washing cycle) only a specific use scenario is considered (coloured clothes or underwear at low temperatures - 30 °C for 7 kg load capacity) and a sensitive analysis for the use phase is necessary to demonstrate the global benefits.

Another important outcome is the possibility to have a certified inverse supply-chain which allows more components and parts to be recovered when the product arrives at end-of-life. This point can reduce the environmental impact of the product-service system compared with the product and also gives the enterprises the possibility to make revenues.

5. Future outlook and concluding remarks

The research moves in the field of service-oriented products in the new marketing and business scenario. Results highlight that the transition from a product-centered perspective to a product-service

one provides great benefits in terms of both environmental and economical sustainability. The obtained results also demonstrate that the proposed methodology can be successfully used to address marketing strategies and support customer decision-making. Furthermore, it can be a valid tool to support the design process of new product-service sustainable solutions: from the conceptual stage to feasibility analysis and end-of-life management. The application of well-known and consolidated methodologies such as LCA e LCC can help designers to conceive and design new service solutions or product+service innovations. It is a new interesting application that serves the modern design purposes, and overcome the traditional comparison of design alternatives.
More case studies could be analysed in order to verify the proposed approach and highlight the strengths and weaknesses. Further analysis in different industrial sectors could validate the method application to support the development of more sustainable solutions, i.e. new services and new product concepts. The final goal is to discover new feasible business scenarios for industrial firms.

References

Byrne J. A., Brandt R., and Port O., "The virtual corporation. The company of the future will be ultimate in adaptability" in Business Week, 1993, pp. 36–40.

Curran, M. A., "Environmental Life Cycle Assessment", McGraw-Hill, 1996.

Davis, M. M. and Heineke, J., "Operations management: integrating manufacturing and services", 5th ed, New York, NY: McGraw-Hill, 2005.

Goedkoop, M., and Spriensma R., "The Eco-indicator 99 A damage oriented method for Life Cycle Impact Assessment Methodology" Report 17 April 2000, Second edition.

ISO 14040, Environmental Management - Life Cycle Assessment - Principles and Framework, (2006), ISO 14044, Environmental Management - Life Cycle Assessment - Requirements and Guidelines, (2006).

Jeswiet, J., "A definition for life cycle engineering" proceedings of the 36th international seminar on manufacturing systems. Saarbrucken Germany. Plenary Speech. See proceedings pp. 17–20, 2003.

Kaebernick H., Sun M., Kara S., "Simplified Life Cycle Assessment for the Early Design Stages of industrial Products", CIRP Annals-Manufacturing Technology, vol. 52, 2003, pp.55-28.

Melk, K., Anderl R., "A Generic Framework for Life cycle Applications" Proceedings of LCM conference, 2007.

Molinari Tosatti, L., "Life Cycle Cost Calculation for Investment Decision in Manufacturing" Proceedings of International Conference on Life Cycle Engineering, 2006.

Nakamura et al. "A waste input–output life-cycle cost analysis of the recycling of end-of-life electrical home appliances" Ecological Economics 57, 2006, pp. 494-506.

Reap, J., Roman, F., Duncan, S., and Bras, B., "A Survey of Unresolved Problems in Life Cycle Assessment Part 1: Goal and Scope and Inventory Analysis," International Journal of Life Cycle Assessment, 13(3), 2008, pp. 290-300.

Sakao, T., "A QFD-centred Design Methodology for Environmentally Conscious Product Design", International Journal of Production Research, Vol.45, 2007, pp.4143-4162.

Thoben K. D., Jagdev H., Eschenbaecher J., "Extended Products: Evolving Traditional Product Concepts", proceedings of the 7th International Conference on Concurrent Enterprising: Engineering the Knowledge Economy through Co-operation, Bremen, 2001.

Woodward, D.G., "Life cycle costing – theory, information acquisition and application", International Journal of Project Management, 15/6, 1997, pp. 335-344.

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