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Product-Service Systems across Life Cycle

Lifespan extension for environmental benefits: a new concept of products with several distinct usage phases

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Abstract

End-of-Life (EoL) strategies, and especially products' lifespan extension, are becoming key issues for more and more manufacturers. Their implementations have to be done from the design stage and may be facilitated with design methodologies and guidelines. However, if a function of the system is no longer efficient enough during its use phase, in such a way that remanufacturing and upgrading may not be considered, the system has reached its final EoL, even if it might have been used for other applications.

To address such kind of situations, the present paper investigates the concept of Design-2-Life (D2L) systems. To do so, EoL strategies will be explored to understand the key issues. Then a clear explanation of D2L concept will be proposed as well as its main characteristics. Finally we will discuss the challenges of this new approach and the advantages to develop it under a PSS framework. The case of batteries used in electric cars will be used to illustrate the concept.

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Keywords: Design 2 Life; repurposing; product life extension

1. Introduction

Products and systems are subjected to different regulations to ensure the minimization of their ecological footprint. These regulations prevent hazards all along the lifecycle of the systems. They are covering all the lifecycle stages, from the raw material extraction to the end-of-life (EoL), even if they are mainly focusing on use and EoL stages. Indeed, some regulations oblige manufacturers to care about EoL [1,2], in terms of reuse, recycling and valorisation mainly. Some are focusing on the use phase [3,4], aiming to reduce the impacts from different inputs - energy, water, etc. These regulations complement one another to ensure fewer impacts on the whole lifecycle of the systems. Another way to minimize the environmental impacts of the system, as mentioned by the European Commission, is to extend the products' lifespan [4]; in most cases, this would lead to decrease all the impacts at the same time.

At the other side of the lifecycle, designers need to

integrate all these aspects to comply with regulations. The primary steps are decisive to ensure fewer impacts during the use phase of the system and when it has to be retired. To help designers all along the design stage, many methods, guidelines and norms are available today: Design for Environment, Design for Remanufacturing, Design for Recycling, Eco-design norm (NF E 01 005), Qualitative Life Cycle Assessment, Life Cycle Assessment, ISO 14062, etc. Depending on the characteristics of the products, the regulations to which they are inclined, and the internal policy of the company, designers can set up EoL strategies - e.g. reuse, remanufacturing, upgrading, etc. - to increase the lifespan of their products and so reduce their environmental impacts. In these design strategies, the Product-Service Systems (PSS) business model (BM) would be much more appropriate to manage products [5]. They are defined as "a marketable set of products and services, jointly capable of fulfilling a client's need" [6]. Thus, PSS focus shift from selling products to services, so that, providers are more

subjected to manage use and EoL phases, which would facilitate take-back and feedbacks from customers, improve the lifespan, and so the environmental and economic aspects [5].

However, those EoL strategies may not be appropriate for all products, especially when the key functions and the overall performances of the system decrease. Our research investigates how to reduce the environmental impacts of such products by increasing their lifespan through multiple applications. In this paper, the focus is to investigate this new concept of Design-2-Life (D2L) systems and understand the main differences between current EoL scenarios. To do so, Part 2 defines the main EoL strategies, their steps and characteristics. Then, Part 3 gives a clear explanation of D2L systems and to draw its main characteristics. Finally we will discuss the challenges of this new approach and the advantages to develop it under a PSS framework in Part 4. The case of Li-ion batteries used in electric vehicles (EV) will be used to illustrate the concept.

2. End-of-Life strategies from literature

In order to define the D2L strategy, different EoL scenarios will be investigated and, more particularly, the strategies that aim to extend products' lifespan.

First of all, it is considered here that the EoL of a system is reached when its user discards it, no matter the product is broken or not. Thus, the system follows an EoL strategy, which has been planned from the design stage or which depends on the product profile. Four EoL strategies are usually mentioned in the literature: reusing, remanufacturing, recycling or disposal - see Fig. 1 from [7]. As it will be exposed, other strategies may be considered as sub-levels of the four above-mentioned. Anyway, they all aim to reduce the environmental pressure of products [8].

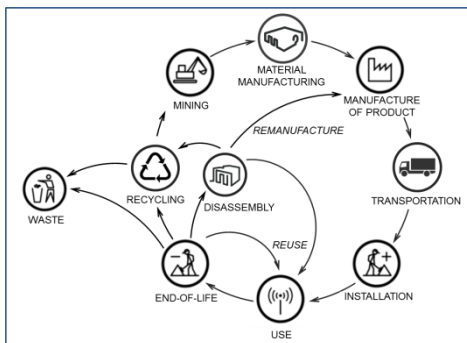


Fig. 1. Classical lifecycle of a system (From Zhang [7])

EoL strategies are influenced by many factors, coming from different perspectives; such as the product characteristics, the process and the BM [5]. In this paper, the BM includes all the surrounding elements set up to perform the EoL strategy (such as the organization, the relationships with the stakeholders, the value creation, the value chain of the offer, etc.), adapted from [9]. These characteristics are specific to each strategy. However, as we focus on strategies to extend products' lifespan, it will be interesting to identify the ones that are similar and those which are different. Indeed, this will help to identify the scope of the D2L strategy and to

better understand the scope of applications. The EoL characteristics will be classified regarding the 3 aforementioned spheres - i.e. product, process, BM - and a rough estimation of their importance regarding the strategy will be made. Furthermore, EoL scenarios usually follow different steps along their life cycle. These steps may be proper to each or shared between some of them - e.g. cleaning, repairing. On the contrary, one strategy as a whole might be included in another. In this second part, the principal EoL scenarios are defined and described in terms of steps and characteristics.

2.1. Reuse

Reusing products consists of collecting them from the waste stream, controlling damages and reusing them for an identical purpose [10,11]. Reuse is mainly possible when the lifespan of some parts of the system are wider than their effective usage [12]. Thus, when manufacturers are reusing a product, they have to worry about its performances: the reused system needs to have the same characteristics and performances than a new one to achieve the same function, no matter the user [10]. In general, these products and components are used as second-hand products or to repair systems - e.g. cars, copiers, etc. - [11] or they are part of another EoL strategy - e.g. remanufacturing - [10]. Consequently, no design methodology has clearly been defined in mechanical literature yet. Nevertheless, some guidelines highlight key criteria to ensure better reuse potential [11]. To facilitate reuse, PSS BM can be used [10]. Thus, different elements would be integrated from design, such as the EoL management.

The reuse strategy is often preferred because its theoretical impacts on the environment are lower than any other strategies [11–15]. Indeed, it doesn't imply any manufacturing activities, such as repair or reconditioning, but only reverse logistic (RL) management. The lifespan of products or components is then extended and environmental as well as financial costs are minimized - in comparison with other EoL scenarios [5]. However, even if it seems to be the easiest way to reduce environmental burdens, it is important to prove that, environmentally speaking, a reused product is better than a new, efficient one [16]. One other important characteristic for reuse is the reliability [13] - e.g. cores of cartridges, furniture for offices, etc. However, as mentioned, this has to be tempered by efficiency gains due to technology improvement [17]. Another characteristic of reused products would be the cost of such option compared to others. Indeed, the reuse tends to postpone the final EoL of the product and thus avoid manufacturing and disposal stages at least once [11,12]. Then, a system may be characterized by the ease of supply - e.g. to take-back products - [12,18] and the easiness of reusing the product [14]. Last but not least, users' profiles would mainly influence the performances of the system at the end of the first use and be determinant for a potential reuse [13].

The above-mentioned characteristics of a reused system are summed up in Table 1. They have been categorised according to the 3 dimensions related to the product, the process or the BM. As stated before, and regarding the EoL strategy, an evaluation of the importance of each characteristic has been done from the authors' opinion.

Table 1. Main characteristics of reused system

Sphere	Characteristic	References	Importance
Product	Reliable product	[5,10,12,13]	VHC ¹
Product	Durable product	[5,11,12]	VHC
Product	High initial cost	[5,11,12,16]	HC
Product	Efficient product	[12,16]	MC ² to HC ³
BM	Ease of reuse	[11,12,14,16]	VHC
BM	Ease of supply	[5,12,16,18]	HC
BM	User profile	[13]	HC
Process	Stable process	[5,12,16,18]	VHC
Process	Stable technology	[5,12,16,18]	VHC

2.2. Remanufacturing:

Remanufacturing activities have been much more studied those past years. Design methodologies, tools and techniques assessing remanufacturing potential, guidelines and lots of case studies have flourished in the literature [12,16,19]. Lund has been the first to define remanufacturing as “an industrial process in which worn-out products are restored to like-new condition” [20]. The main objective is to capture the added value from the initial manufacture of the product and reuse it as much as possible [5,18]. Charter and Gray [5] distinguished 3 main dimensions to describe remanufacturing activities: the product, the process and the BM. The product area concerns all the components themselves, their rearrangement and their main characteristics. The remanufacturing process consists of the different steps set to provide as-new products; such as core collection, disassembly, cleaning, sorting and controlling, reconditioning and reassembly [19]. The BM covers the global strategy of the remanufacturing activities - e.g. RL management, product payback, etc. - [19]. Remanufacturing, such as reuse, may be performed through PSS BM. The shift from selling products to providing PSS would imply: the improvement of the management of the use and EoL phases, as well as the necessity to find retirement solutions, which may lead to improve environmental, economic and social aspects of the offer [10,12].

Remanufacturing is seen as “a combination of new and reused parts” [19]. The literature identifies the reuse strategy as part of remanufacturing [11]. Fundamentally, this means that most parameters associated with the reuse strategy shall be included in remanufacturing scenarios. That is why, concerning the product, remanufacturing literature states that reliable and durable systems – or at least part of them – are necessary to ensure remanufacturing [5,12,19]. Their initial costs are quite high, thus remanufacturing is an economic viable option [5,11,12,16,18,19]. As mentioned by Gray and Charter and Go et al., when reaching their EoL, these products fail functionally, rather than being dissolved or else [5,12]. Remanufacturing is also facilitated if the systems are efficient all along their life cycle [16,17]. Bakker et al. precise that “products with high use energy compared to embedded energy should be replaced

frequently” [17]; that is why, (partial) upgrades may be used to ensure the as-new functionalities of the product [5,19]. The last main points concerning the product and mentioned as key issues are the numbers of parts and modules of the remanufactured system and the number and types of fixations. These elements will mainly influence the assembly and disassembly steps during the remanufacturing process. It’s during this process that the remanufacturer is able to preserve, partly or fully, the added value due to the manufacturing stage [5,16,18]. So that, it requires a stable process over the years as well as a stable technology [5,12,16,18,19]. The process will also be facilitated if the major part of the systems is going through the RL. Thus, the BM needs to match the last parameters. To do so, the easiness of reuse of the system and the availability of supply are prerequisite [12,16]. The users’ profiles are also an important condition. Zhao [13] shows that the users are significantly influencing the performances of the products and thus their lifecycle. Customers, or any actors all along the value chain, may also be a driver for remanufacturing and impulse this BM [16,18,19]. For example, customers may prefer low-priced-remanufactured products rather than brand-new ones. Remanufacturing may also be a response to a legislation concern [5,11,19]. As mentioned previously, remanufacturing could be a more sustainable way to valorise product than disposal or even recycling [14]; and, if the remanufacturing process may not be fully handle by the manufacturer, it will be the occasion to create partnerships - e.g. to ensure the RL, the disassembly, the control, etc. - [10].

The above-mentioned characteristics of a remanufactured system are summed up in Table 2. They have been categorised according to the 3 dimensions related to the product, the process or the BM and an evaluation of the importance of each characteristic has been done from authors’ opinion.

Sometimes, products’ EoL may be related to remanufacturing without being called as such. For example, upgrading strategies are based on modular design and aim to maintain or improve performances of systems all along their lifecycle by the integration of partial upgrades [13]. It may concern products’ components, parts, or functions. In a more general way, modular design may be used when there is a need for rapid replacement. Thus a new or repaired part may be installed instead of the damaged one to quickly fix the problem [17].

Other EoL strategies, such as repairing or reconditioning are considered as steps of remanufacturing. Apart from remanufacturing, repairing consists in returning a product as a working condition, usually for the same user. In the same manner, reconditioning implies to “return a used product to a satisfactory working condition” [17]. Nevertheless, because this last one doesn’t bring the system back to as-new conditions, it might be considered as borderline with the remanufacturing strategy.

2.3. Other End-of-Life strategies

Reuse and remanufacturing aren’t the only EoL strategies. Recycling and disposal are also two main EoL strategies for products [14]. Usually, even if reuse and remanufacturing are set up, recycling and disposal need to be considered. Indeed, at some point, standard systems can no longer pretend to be reused or remanufactured. Then, a non-life-extension strategy

¹ VHC : Very High Concern

² MC : Moderate Concern

³ Depending on the system, the importance of this characteristic may vary from MC to HC

Table 2. Main characteristics of remanufactured system

Sphere	Characteristic	References	Importance
Product	Reliable product	[5,10,12,13,19]	VHC
Product	Durable product	[5,11,12,18,19]	VHC
Product	Functional problem	[5,12]	HC
Product	High initial cost	[5,11,12,16,18,19]	HC
Product	Efficient product	[16,17]	MC to HC
Product	Modularity / Upgradability	[5,18,19]	MC to HC
Product	Physical elements ⁴	[12,18]	MC to HC
BM	Ease of reuse	[11,12,14,16]	HC
BM	Ease of supply	[5,12,16,18,19]	HC
BM	Economic motivations	[5,11,12,16,18,19]	HC
BM	User profile	[13]	HC
BM	Remanufacturing reason (customer, etc.)	[16,18,19]	HC
BM	Partnership	[10]	MC to VHC
BM	Legislation	[5,11,16,19]	HC
Process	Stable process	[5,12,16,18,19]	VHC
Process	Stable technology	[5,12,16,18,19]	VHC
Process	Remanufacturing flow ⁵	[18]	MC to HC

will have to be selected. However, they will no further be studied as they don't contribute to extend products' lifespan.

2.4. Outcomes

In a general way, product life extension has to be supported by multiple characteristics, from the product, the process and the BM. Bakker et al. [17] stated that product life extension is possible for products subjected to resource intensity and with mature technology. It is even more clear when regulations and market competitiveness are steering companies to do so [17]. However, products need to be reliable, durable - emotionally, aesthetically and functionally - and energy-efficient all along their extended life [17]. Thus, performances of products should not decrease over time with a need to ensure the well-functioning of the product all along the different uses.

Zwolinski et al. [18] showed that remanufactured products may correspond to different profiles. If characteristics of remanufactured products vary from one to another, the remanufacturing strategy would be hardly applicable when one of the main characteristics is missing. So, direct reuse or even remanufacturing are not viable End-of-Use (EoU) strategies for every systems. When systems are arriving at their functional obsolescence, they have to be discarded, while if a second application requiring reduced performances is defined from design, the lifespan of the system can be extended.

3. Design-2-Life strategy

3.1. D2L Concept

Extended-life strategies, such as reuse and remanufacturing

⁴ Those include different characteristics such as number of parts, number and type of fixation, etc.

⁵ Number of remanufactured products over the whole amount of products.

may generate sustainable gains but are not applicable to all products; so that the present paper investigates the concept of D2L systems.

As it is understood here, a D2L system should support several distinct use phases, at least two, and thus extend its lifespan to reduce environmental impacts and overall economic issues. Foster et al. [21] described these kind of systems as repurposed ones, which means that there are reused for different application than the former ones. There are different key issues to define them.

Firstly, the main functions should not vary much from one use to another. Indeed, even though the performance criteria may be radically different, the system has to fulfil the same need. In the case of Li-Ion batteries, the first intended use would be to store energy for EV and the second one would be to store energy for stationary application.

Secondly, RL has to be planned from the design stage or, at least, be sure that it would be possible through partnerships. This would enable take-back of products between each EoU and the next use. Thus, the supply of used products will be ensured.

Thirdly, providers need to plan the manufacturing steps which would be required to ensure system performances between any EoU and the next use. Fig. 2 shows what could be the lifecycle steps of a D2L. At the EoU 1, the product will be disassembled, the worn-out part recycled or discarded and the system will enter in its 2nd lifecycle. In essence, repurposing steps should be simple and not require heavy manufacturing steps. They should be profitable in terms of money and environmental impacts in comparison with other EoL strategies such as remanufacturing, recycling or disposal. Through the same example of Li-Ion batteries, repurposing steps might be: preliminary testing, disassembly of the main components, cleaning, reconfiguration and assembly of components dedicated to the second application and final testing.

Finally, all these different points have to be defined from the design stage to integrate the different requirements as soon as possible and optimize environmental impact as well as economic gains. If such systems are already on the market - e.g. the EV batteries -, it is going to be more difficult to apply the D2L strategy, but it is important that it still remain possible. The EoL strategy will have to deal with existing products.

3.2. D2L main characteristics

D2L systems, or repurposed systems, as well as reused or remanufactured ones, should be described through different characteristics. These are pointed out in terms of product, process and BM hereinafter.

Concerning the BM, one driver for repurposed products may come from the states through regulations. Some encouraging reuse and remanufacturing; repurposing is another way to extend lifespan of products which may prevent from additional environmental cost. Another element to care about is the availability of supply for the next use. Indeed, to ensure the repurposing of any system, it is important to know how to manage RL and in which way the take-back of products will be done. RL may be realised directly either by the 1st use provider, the 2nd use provider, or by a third party through partnership. Then, to ensure repurposing activity working, the price of the repurposed product will have to be

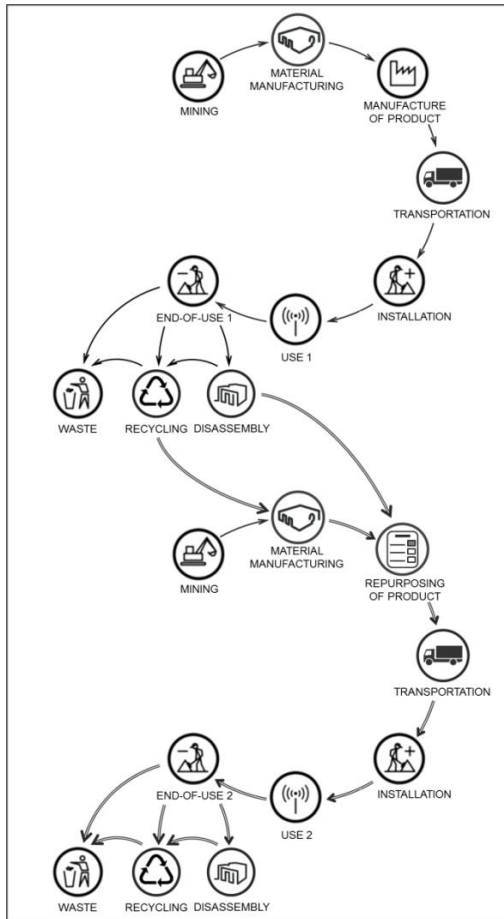


Fig. 2. Interlinked lifecycle of a 2-usage D2L product (adapted from Zhang)

lower than the brand-new one. As the system would be considered as a second-hand product, with probably decreased performances, and because additional costs will mainly be caused by RL and additional manufacturing steps, the price of a D2L would not be as expensive as a new system. Foster et al. [21] studied impacts of the remanufacturing, recycling and repurposing of a Li-Ion battery system. The first use was to power an EV. In this case, repurposing activities would have been for alternative energy storage applications. Foster et al. stated that, because repurposing applications are not defined at first, it will lead to research and development costs. To remain competitive, these costs should remain lower than 55% of the sell price. The need to define different uses from the design phase is important. This would facilitate and optimize the whole process. However, it seems difficult to plan the next uses and, in any case, repurposing methodology needs to be applicable to existing products. So that, if D2L systems are designed to facilitate reuse, it will help the manufacturing steps between the different uses.

As it has been introduced, different steps have to be followed during the repurposing process. Firstly, products need to be tested to evaluate their performances after the first use. Thus, diagnostics of performances will determine the repurposing steps. Indeed, depending on the use of the systems, the performances might be different from one to another. D2L products may have to be reconfigured to fulfil their 2nd usage. For example, a Li-Ion battery used at first in

an EV and repurposed for stationary application will need different performances, in terms of depth of discharge, number of cycles or else. In the best case, the design phase will consider the two different uses and define how products have to be designed and reconfigured; otherwise designers will have to integrate the characteristics of current products and repurpose them for the 2nd use. To make the repurposing easier, products should be easy to disassemble and to reassemble. Finally, unless others EoL strategies such as remanufacturing and reuse, D2L strategy should not be reserved to stable processes and technologies, but also to emerging ones. Indeed, reuse and remanufacturing aim to reach like-new conditions. When this isn't possible, because products performances are not satisfying enough to ensure the same function than in the 1st use, then repurposing would be a pertinent strategy. Indeed, repurposing the system in another application should be more environmentally-friendly than recycling or discarding it.

Concerning D2L products characteristics, reliability, durability and energy-efficiency to fulfil different needs and customers would facilitate repurposing strategy. Furthermore, repurposing systems could concern expensive products, especially when the remaining costs at the 1st EoU are quite high. Modularity of products may improve the repurposing process to move from one use to another. Finally, on the contrary to the other strategies, the EoU would be the result of a functional problem, in terms of performances. In fact, when the performances of the product would no longer fit the required specifications, it would reach its EoU. However, this would not be such an issue for D2L products as the next use would require lower performances.

The 3 spheres show some differences between usual product life extension strategies and D2L. D2L products should fit 2 distinct usages, where the second use would require lower performances than the first one. Because the second use might not be known from the design phase, the repurposing process will have to be adjustable for each particular product and products should be easily inspected and tested. Furthermore, repurposed D2L might be more subjected to be provided through partnership than reused or remanufactured ones. Thus, RL need to be in place. Finally, D2L may concern stable technologies as well as emerging ones. When direct reuse and remanufacturing are not convenient alternatives, D2L may be the answer.

4. Discussion

4.1. EoL strategies and PSS: challenges

EoL strategies are on a roll. Many drivers are pushing them forward: the current need for resource efficiency, extension of producer responsibility, etc. One way to reach these obligations is to increase the lifespan of products and ensure their retirement. Current EoL strategies, mainly reuse and remanufacturing, are good ways to achieve it; using PSS framework would help to deliver the offer. Indeed, reuse and remanufacturing are already close to PSS. They all need RL chain management, infrastructures for products take-back and usually require partnerships. They imply stronger relationships with customers than a selling interaction only.

They also have the advantage to maximize products lifespan, implying direct profit for D2L providers and leading to potential environmental gains.

D2L is another product life extension strategy addressed to systems that wouldn't fit for reuse or remanufacturing. Delivering D2L systems through PSS would have many advantages. Firstly, PSS would be as good for repurposed systems as reuse and remanufacturing, as we saw just before. PSS would ensure a better use of products. Indeed, providers may propose services to maintain or improve the product during the use phase. So, they would have more information about the performance evolutions along its lifetime and will improve them. Furthermore, PSS would facilitate the RL chain management by defining, from the design phase, how to get products back. Within PSS framework, information about the state of health of the system would be easier to collect during the use phase. So that it would facilitate RL and repurposing steps. Secondly, if D2L systems are designed for PSS, the next uses could open new businesses and diversify activities for D2L providers. Contrary to reuse and remanufacturing, this also may decrease the cannibalisation phenomenon which sometimes appears in these EoL strategies. As the provider would manage the product on its whole lifecycle, it will be able to determine the best supply for the next use, from the design stage. The future uses may also be carried out through partnerships. It would be easier to find and develop partnership under a PSS framework to handle the activities which are out of the scope of the company - e.g. maintenance on-site, RL, repurposing step, etc. Indeed, providing services rather than products should open the scope of possibilities in the way the offer may be delivered - e.g. more robust design, closer customer partnership, innovative offer management, etc. Such as other EoL strategies, legislation may be a driver for D2L systems.

4.2. Current obstacles

Nowadays, only few examples of applications of repurposed products are present in the literature. Furthermore, the majority of them are related to EV batteries and, even here, the economic feasibility is not expected [22]. D2L mainly needs research and development to facilitate the repurposing of products [21,22]. Consequently, and because no design methodology currently exists, the first step will be to dig further for drivers of successful D2L in the Design for X literature and in other repurposing case studies. One of the hotspot to get around is the fact that the 2nd use might still be vague when designing the product at first. Modularity and flexibility of the repurposing process would be necessary, especially if products are already on the market. The last point is the need to assess the environmental impacts of the system and compare it to other solutions to be sure that D2L systems will be the most environmentally-friendly solution. To do so, Life Cycle Assessment would be used even if it still remains some questions about how to define the functional unit.

5. Conclusion

In this paper, a new EoL approach has been proposed. The concept of D2L leans on others EoL strategies such as reuse and

remanufacturing. The main difference comes from the nature of the next use: when the product performances are not fitting the former use anymore and when an adequate remanufacturing process isn't established, the product should be repurposed in another application, needing different levels of performances. This 2nd life would prolong the lifetime of the product to decrease its overall environmental impacts. Using a PSS framework should be an advantage to develop such systems, mainly in term of RL, repurposing steps, regulation and partnership facilitator.

Further studies will help to define a methodology to design and repurpose products.

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