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Stay in the loop: the role of indicators in supporting decisions for circular economy strategies aiming at extending products life

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Abstract

Circular economy proposes an innovative "circular" model towards increased sustainability. The central tenet of circular economy is to move away from linear practices ("take-make-use-dispose" approaches) towards the continuous "cycling" of products, materials and resources. Circular economy can be achieved by adopting practices that include solutions for a) intensified use of products (e.g. product pooling and sharing); b) circular product design (dematerialised products; designed for longevity, reparability and recycling); c) material and resource "cycling", and more. Along with radical transformation of business models and value chains, product design is of the essence to effectively support circular economy transitions. The EEA report "Circular by design" from 2017 on products in the circular economy highlights that designing products using clean materials or increasing use of modular design is "a prerequisite for circularity". Design stage, therefore, is crucial in "initiating" circular shifts; however, the strategies that aim at extending life cycles of products that are currently on the market are as significant. The European Commission made a resolution on a longer lifetime for products (2016/2272(INI)) stressing the urge for extended producer responsibility to tackle the issues of durability, reparability and recyclability of tangible consumer goods.

This article aims to provide an insight on how the sustainability related performance indicators can support decision making for circular economy strategies aiming at extending life time of existing products, components and materials (through service, repair and recycling) taking a cross-business process view. The article provides an example of indicators and their application to a hypothetical case study. We follow the indicator selection procedure, with the help of which the set of relevant indicators is selected for the CE initiative assessment. By taking a case example, we demonstrate i) the importance of operating with indicators across business processes; and ii) the importance of a dynamic indicator set (as opposed to the 'prescribed' indicators). Based on the final performance indicator set relevant for the case, the decision can be made to either implement the strategy, select/combine with another or avoid the implementation altogether.

Keywords: circular economy, extending life cycle, performance indicators, decision making for sustainability

1. Introduction

Products play a key role in the European economy, providing the service and functions to the society to satisfy their needs. It is reported that worldwide two-thirds of the adults use the Internet, in Africa and South Asia a smartphone being a main device to provide such access (Poushter and Stewart, 2016). Mobile technologies and services generated 3.3% of GDP in Europe alone, serving around half a billion of mobile subscribers (GSMA, 2017). Despite the economic and social benefits products and services bring, products and down- and upstream activities associated with them, such as raw material extraction, production, distribution and use, and disposal contribute to other global and local environmental pressures, such as resource depletion, air, water and soil pollution, waste generation (OECD, 2003). For instance, the mobile phone system consumes annually approximately 2200 GWh of electricity in Italy, which is equal to around 1% of the national electricity consumption (Paiano et al., 2013). The growth in gross national income per capita in Europe has also been correlated to an increasing municipal solid waste generation (Geyer et al., 2017), which for some European countries (e.g. Denmark, Greece, Malta) more than doubled from 1995 to 2017 (Eurostat, 2017). This challenge can be overcome by adopting a circular economy (CE) model, in which the value of products, materials and resources is maintained for as long as possible, consequently contributing to a low-carbon and low waste economy (European Commission, 2015). In this context, designing products that are durable, repairable and recyclable is crucial for the development of CE. Large body of the literature (McAloone and Pigosso, 2018; Nielsen and Wenzel, 2002) conclusively states that the design stage plays a key role in influencing the product's environmental impact during its whole lifetime. By adopting eco-design principles, the manufacturing industries will be able to improve the environmental performance of the products without compromising the costs, quality and performance (Issa et al., 2015); furthermore, eco-design can stimulate transition to CE by providing guidance on the design of products for reparability, durability, upgradability and recyclability (European Commission, 2015).

Despite eco-design being recognized as one of the promising management approaches for environmental sustainability (Fernandes et al., 2017), several studies, focusing on product design for CE (den Hollander et al., 2017; Moreno et al., 2016), have argued that eco-design may not be sufficient as a sole approach to address the complexity of aspects product design for CE should be based on. In their interpretation, product design for CE should extensively take into consideration human-related aspects as opposed to a technical perspective, which is dominant in eco-design approach (Bhamra et al., 2011). The argument is stipulated by a discussion of the premature product obsolescence, which product designer can influence by considering both, the technical (physical) durability and the emotional durability, i.e. the durability that occurs when the product is designed to induce attachment of a user to it (den Hollander et al., 2017). Indeed, as Prakash et al., 2016 (in (European Environment Agency, 2017) found, in Germany in years 2012-2013, "30 % of white goods purchased replaced an appliance that was still functioning — the decision to buy a new product was motivated solely by the consumer's desire for an upgrade". For clothing, the desire of a consumer to purchase a new item has been linked to a relatively low price to acquire an item and 'fast fashion' cycles (EMF, 2017).

Furthermore, the myopic, solely product design, perspective, is not enough to obtain the benefits the CE is projected to achieve (Bocken et al., 2016).

Circular economy implies a systems perspective, where production and consumption systems both need to be redesigned to function in a circular way; for the manufacturing industry, accordingly, it requires introducing simultaneous changes in multiply business process, including business models, forward and reverse logistics, manufacturing, product design and development and others (Lieder and Rashid, 2016). To guide the manufacturing companies in transition to CE, (Pieroni et al., 2019) developed a configurator for opportunities and designing business model concepts for circular economy; (Van den Berg and Bakker, 2015) proposed guidelines for product design in circular economy; while other authors suggest a more synergetic development, like a product and business model design framework for circular economy (Bocken et al., 2016), a framework to integrate circular business models and circular supply chain management (Geissdoerfer et al., 2018), etc. Despite a wider recognition to address synergetic development of products with business models and value chains for CE (see more by (den Hollander et al., 2017; Moreno et al., 2016), there is a lack of methods to assist manufacturing companies in providing a comprehensive support in doing so (Pieroni et al., 2018). Such support is needed to ensure that the circular 'goodness', embedded in the product, is harvested for environmental and economic benefits of the company's business ecosystem. For instance, for a product, designed to be remanufacturable, a system has to be set up to allow the products to flow back to the focal (controlling the value chain and the brand) company to be remanufactured, thus requiring a new business model and reverse operations system to be designed accordingly. For the company, therefore, there is a strong potential to systematically capture and retain the economic value of the product over time (den Hollander et al., 2017). This is particularly essential in order to realize the European Commission's resolution on a longer lifetime for products (2016/2272(INI)), which stresses the urge for extended producer responsibility (EPR) to tackle the issues of durability, reparability and recyclability of tangible consumer goods. Although the EPR legislation, which requires producers to take responsibility for their product after post-consumer stage of a product's life-cycle, is intended to provide incentives for producers to design products for easier disassembly and recycling, several studies point out at its limited effectiveness on incentivizing the extension of product's life through repair and remanufacture (Kunz et al., 2018). EPR has had most influence on waste collection and recycling (partially because of setting targets for recycling), but not on incentivizing repair or remanufacturing (due to the lack of targets and indicators for repair, reuse, remanufacturing) (European Environment Agency, 2017; Kunz et al., 2018). Furthermore, some authors (Huang et al., 2019) argue that EPR can (unintentionally) have counterintuitive design implications for durable products, stating that "stringent recycling targets incentivize producers to design for durability, yet this may come at the expense of product recyclability. In contrast, stringent collection targets incentivize producers to design for recyclability, yet this may come at the expense of durability" (p. 2574). These regulations, and, consequently, design choices, can hinder realisation of circular economy strategies and impact their sustainability performance (Kunz et al., 2018). CE impact on sustainability performance should be measured prior, during and after CE implementation to understand its 'potential' and 'actual' sustainability contribution (Korhonen et al., 2018), however there is a lack of assessment tools to support such assessments (Kalmykova et al., 2017), specifically to be used by industrial practitioners (Kravchenko et al., 2019).

Considering the complexity of decisions the manufacturing companies need to take to design their products and business models for CE, and the importance of these decisions to incorporate sustainability considerations and be supported by sustainability measurements, we provide a study on the deployment of a set of tools to support selection of relevant leading sustainability-related indicators for measuring potential sustainability performance of the CE strategies that aim at extending products life (such as repair and maintenance and recycle). We follow the indicator selection procedure, with the help of which the set of relevant indicators is selected for the CE initiative assessment. By taking a case example, we demonstrate i) the importance of operating with indicators across business processes; ii) and the importance of a dynamic indicator set (as opposed to the 'prescribed' indicators).

2. Methods

The section provides on overview of the conceptual framing – a tool and a procedure developed in earlier research stages to support quantitative sustainability assessment of CE initiatives. We then proceed to presenting a case company, which help us demonstrate the applicability of the selected tools.

2.1. Leading sustainability performance indicator database and the selection procedure

The Leading sustainability performance indicator database comprises a repository of 270+ leading performance indicators that are classified according to three major elements: organizational business processes, CE strategies, and TBL dimensions and aspects (Figure 1, (a)). For the CE strategies layer, a list of strategies have been compiled and elaborated on from the CE framework by (Potting et al., 2017). This framework has been selected based on its inclusion of a wide range of CE strategies relevant for the manufacturing context (not sector-specific) and provision of definitions of these strategies. The list consisted of thirteen CE strategies, which range from dematerialisation and product-service system strategies through recycling and recovery. For the business process layer, five major business processes have been considered: business model, product development, production & operations, after-sales service, and end of life operations. These processes are typical for any manufacturing company (Ray et al., 2004). The business process layer allows to retrieve indicators relevant to measure during business processes affected by the CE strategies in focus. This construct enables an integrated consideration of CE strategies across various business processes. For the sustainability layer, three dimensions from the TBL view were considered (environmental, economic and social), with multiply aspects covering each dimension. As a result of the indicator collection and classification (described in detail in paper by Kravchenko et al. (2019a, in review for JCLP), each CE strategy is covered by a range of leading performance indicators, which can be used to analyse the potential economic, social and environmental performance. The consolidated database of leading sustainability-related performance indicators provides industrial practitioners, who express their interest in understanding the sustainability considerations and implications of circular economy initiatives by means of employing quantitative sustainability indicators, with a systematized repository, which reveals what indicators are relevant to measure for each CE configuration (i.e. a combination of a CE strategy/ies and a business process) (Figure 1, (b)), as well as what dimension of sustainability the performance is being measured (Kravchenko et al., 2019). Figure 1 shows the abstract representation of the 'Leading performance indicator database' layout: (a) classification criteria for leading performance indicators; (b) a set of N number suitable indicators available for the selected CE configuration i (a combination of CE 'reduce impacts in raw material and sourcing', CE 'reduce impacts in manufacturing' and a business process 'production & operations'). A database is accessible in an Excel format at the web-address https://doi.org/10.11583/DTU.8034188.v1 .

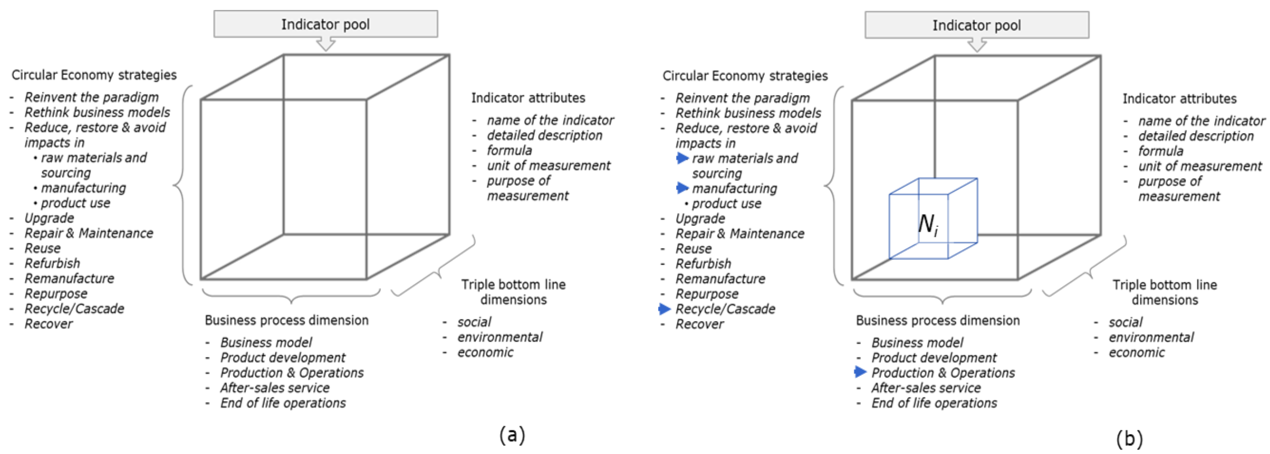

Figure 1*. The abstract representation of the 'Leading performance indicator database' layout (a) and indicator selection logic (b).*

In order to select a set of suitable indicators for the case presented in this research, the indicator selection procedure was followed. The indicator selection procedure has been developed to assist an industrial practitioner in a meaningful selection of suitable indicators available from the indicator database (Kravchenko et al., 2019b, in review). The procedure takes into consideration the complex nature of circular economy by allowing the user a dynamic selection of indicators based on the combinations of multiply circular economy strategies and business processes relevant for the case as well as its contextual settings (product, industry, sustainability aspect of high concern, etc.). The indicator selection procedure has been empirically evaluated through a case study approach, with the final version available in (Kravchenko et al., 2019b, in review) and as presented in Figure 2. To work with the indicator selection procedure, a combination of CE strategies and business processes needs to be defined (Step 1), thus serving as an input to Step 2, where the inputs need to be applied by setting filters in the 'Leading performance indicator database'. As a result, an initial indicator set will be established. Several sub-steps under Step 2 have to be executed to gradually select indicators for the final set (Step 3). For the sub-steps under Step 2, the user team have to comprise the people with substantial knowledge of business processes that are in focus (identified in Step1) and sustainability or environmental managers, who have expertise in working with sustainability projects. Finally, it is important to implement the final set of indicators in order to understand the performance of the selected CE initiatives by comparing them with the baseline situation.

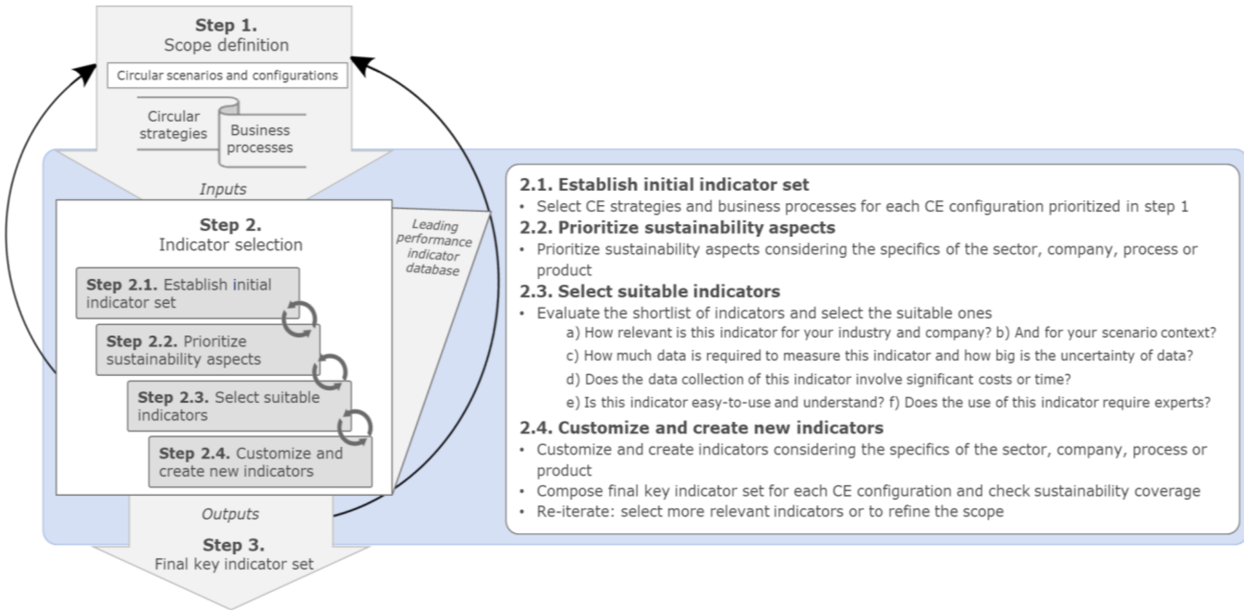

Figure 2. *The procedure for a systematic indicator selection for CE sustainability performance measurement*.

2.2. Case presentation

We present a case, which was set up to be used to retrieve a set of relevant indicators applicable for the CE strategies aiming at extending products life considering an integrated business process approach. The results, consequently, show to what extent the 'contextual' boundaries influences the number and type of indicators to be used to measure the potential sustainability performance of the selected CE strategies. Circular economy is a complex and multifaceted phenomenon (Potting et al., 2017) and a specific case settings allow to have the circular economy phenomenon explored in its 'contextual' boundaries, i.e. how it is being operationalized and measured using sustainability-related indicators.

The case company, CarpetCo, belongs to the manufacturing industry producing carpets for residential buildings, non-residential buildings (business and governments), and transportation service. The carpet manufacturer case was selected for this study due to relative product durability, complexity (variety of materials) and low recycling rates (Wilts et al., 2017), as well as representing the sector of 'uncertain' circularity potential (EMF, 2013; European Commission, 2014). While the global demand for carpets is rising (totalled 4.45 billion square meters in 2014), the most common end of life scenario is still landfilling (60 % in Europe) and incineration (Wilts et al., 2017). This can partially be attributed to the complexity of the product, because of the variety of materials, synthetic and organic fibres and resins that are bonded by adhesives together (Miraftab et al., 1999). This challenge is further aggravated by the fact that carpets need to be maintained during their use, which often requires application of cleaning equipment (e.g. vacuum cleaning and detergents). Considering the challenges, CarpetCo wants to introduce CE initiative to reduce premature product obsolescence and waste generation by considering a CE solution, which comprises the offering through a product-service system, with product support in use and recycling at the end of life (Table 1).

Table 1. *Background information about the case company, CarpetCo.*

Sector	Customer segment	Current business concept	Circular vision and objectives
Carpet producer	B2B, EU market	'Single' sale of quality carpets, made of three layers: 1st : nylon, 2nd – latex glue, 3rd - polypropylene	Circular vision is to establish a long-term relationship with customers by providing long-life support for their products. Circular objective is to reduce premature product obsolescence, waste generation and increase customer satisfaction. The CE initiative comprises the offering through a product-service system, which includes product leasing, installation, repair and maintenance, and removal at the end of use for recycling.

With this background information, the procedure for a systematic selection of suitable sustainability-related performance indicators for circular economy strategies screening was employed. The Excel database of leading performance indicators was used as a tool to retrieve the initial indicator sets considering the specifics of the case. The indicator database and the procedure are described in subsection 2.1. The indicator database and the procedure were employed internally by a research team acting as a case company representatives.

3. Results and discussion

With the background information on CarpetCo's CE vision, a set of CE configurations have been defined (Figure 3). A CE configuration is a combination of one or several CE strategies and a business process. CE strategies are identified together with the company using a CE strategy framework adopted from Potting et al. (2017). This exercise helped to align what circular solutions the company considers as well as to bring more clarity about what each CE strategy entails. For instance, with the help of definitions provided in conjunction to the framework, CarpetCo's CE solution of developing a PSS was found to belong under CE strategy 'Rethink and reconfigure business models'. In this strategy, the focus is placed on making product use more intensive by rethinking the way of delivering it's function (by selling it's performance or delivering result) and/or value proposition through product leasing, renting, sharing, pooling (Blomsma et al., 2019, in review). By switching to a PSS, CarpetCo's intention is to retain product ownership so the product can be serviced during use, but also retrieved at the end of its use. Using the CE framework, following CE strategies have been identified: 'Rethink and reconfigure business models' (as explained earlier), 'Reduce impact in raw material and sourcing' (because the solution was to use own recycled carpets as a substitute for virgin input), 'Repair and maintenance' (because of the intention to provide cleaning, repair and maintenance service during carpet's use), and 'Recycle' (because carpets would be internally recycled to be used for making new carpets). Business process consideration helped to understand how the identified CE strategies could be operationalized. For instance, a business model has to be redesigned to explain the logic of creating, delivering and capturing value (DaSilva and Trkman, 2014), an 'after-sale service' has to be set up to allow execution of the service planned in the PSS. Furthermore, 'end of life' operations should be organized to manage a product after its removal from the customer at the end of its use cycle (e.g. collection and recycling). From a product design perspective, it may be important to ensure the products is suitable for the proposed CE solution. Therefore, a 'product development' layer can be brought in in conjunction with the prioritized CE strategies ('Repair and maintenance' and 'Recycle') to select indicators to measure how well does the product suit the solution, but also to highlight what has to be measured to (re)design a product to fit the proposed PSS. Following this logic, a set of CE configurations have been set up to identify what indicators are available to measure the potential sustainability performance of the selected CE initiative (Figure 3).

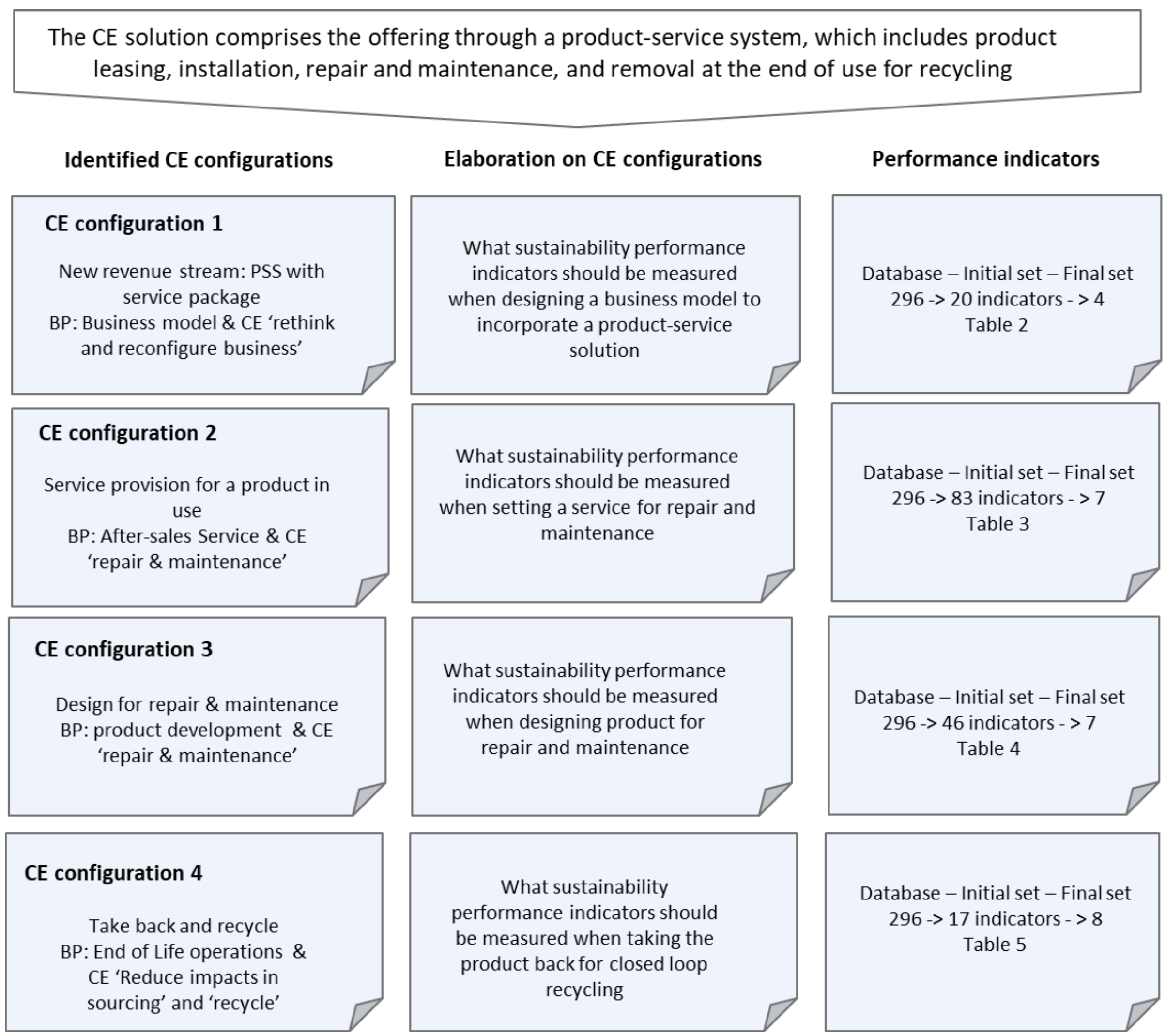

Figure 3. *A set of CE configurations relevant for CarpetCo's CE initiative.*

CE configuration 1 has been defined based on the need to change a business model, with new value proposition to the customer, such as increased product support and maintenance during leasing period and 'care-free' product removal at the end of use. Considering this, an initial set of indicators has been identified (Figure 3), followed by a process of indicator selection for the final set. To select the final indicators, a set off questions were used to guide the process. The questions are listed in Figure 2, under step 2.3. and are as following: a) How relevant is this indicator for your industry and company? b) How relevant is this indicator for your scenario context? c) How much data is required to measure this indicator and how big is the uncertainty of data collection? d) Does the data collection of this indicator involve significant costs or time? e) Is this indicator easy-to-use and understand? f) Does the use of this indicator require experts?. By reviewing the initial indicator set, a final set consisted of four indicators. Four key indicators have been selected reflecting the need to understand how the performance will potentially be impacted when changing to product ownership model and providing supporting services. For instance, the indicator 'Product ownership cost in business' has been selected to understand what costs CarpetCo would incur by retaining ownership of leased carpets and providing supportive services. This can potentially signal about the need to re-design a product to ease its installation, maintenance and removal to cut cost of ownership. Furthermore, it was also important to help customer to make the decisions in engaging in leasing, therefore, the indicator 'Product ownership cost for the user' has also been selected. Due to the fact that no environmental indicators could be retrieved for a business model layer (Kravchenko et al., 2019a, in review), a more 'operational' CE configuration, which implied setting a service for repair and maintenance has been used to understand the environmental implications of service provision. The 'Leading sustainability performance indicator database' contains description of indicator attributes that assisted users in understanding each indicator, what is measures and how it is measured (available at web-address https://doi.org/10.11583/DTU.8034188.v1).

Table 2. *A final indicator set for CE configuration 1.*

Nr	Indicator name	CarpetCo comments
1	Product ownership cost in business	Important to determine the direct and indirect costs of offering the PSS scheme (i.e. leasing model with service and maintenance and removal). It can be that the carpet has to be re-designed to ease cleaning and maintenance
2	Maintainable period after sales	A contract duration with a customer is important to establish a long-term relationship
3	Product ownership cost for the user	Important to help customer to make the decisions in engaging in leasing
4	Job creation per unit of product	Important because services associated with product service and maintenance require labour, also close to the user of the product

CE configuration 2 has been defined based on the new business model of product-service system, which implies installation and service provision like cleaning, repair and maintenance. CarpetCo, therefore, was interested in understanding what sustainability performance indicators should be measured when setting a service for repair and maintenance, so to ensure possible changes to the process or product can be introduced prior it is actual implementation. As a result of the indicator review, the final set of performance indicators consisted of 7 indicators (Table 3). Most of the indicators addressed the costs associated with service provision (e.g. labor cost and energy cost), however the costs of water, energy and cleaning agents can directly be linked to resource consumption, therefore, acting as indicators measuring performance on both, economic and environmental aspects (Kravchenko et al., 2019). During the indicator review process, the indicator 'Duration of product use' has been selected by the company to understand how service provision and maintenance can affect the carpet's useful life; in addition, the indicator 'Replaced parts' has been added to the set because the company realized that the carpet may need to be redesigned to allow replacement of some worn out parts instead of replacing the whole carpet. These indicators have been identified important to help understanding how CarpetCo's CE objective to reduce premature product obsolescence can be achieved.

Table 3. *A final indicator set for CE configuration 2. Social indicators have been deselected for this CE configuration, because the company has a control over work and employment conditions.*

Nr	Indicator name	CarpetCo comments
1	Labor cost per unit of service	This indicator measures the cost associated with cleaning and quality check. We need to ensure there is cost effectiveness in service delivery for our product
2	Duration of product use	Important to understand the difference of our product's durable life from the market average
3	Cost of water during use phase of the product	Helps to understand water usage during service provision (e.g. for cleaning)
4	Cost of energy during use phase of the product	Helps to understand energy usage during service provision (e.g. for cleaning)
5	Time for service provision	Important to decrease waiting time for the user by establishing local service points and by training servicemen to provide service
6	Cleaning agents used by service providers	Important to measure amount (type) of cleaning agents for service provision. Decreasing this amount can avoid harm to the environment and decrease costs
7	Replaced parts	Can we replace worn out parts of the carpet without replacing the whole carpet?

CE configuration 3 has been defined following the company's intention to understand what has to be measured when designing a product to be repairable and maintainable, so to understand how well does the product fit into the new business model. Indicators 'Number of modules' and 'Time for worn part replacement' have been found very important as they will define how to design a carpet to ease accessibility of worn parts, thus facilitating the process of their replacement and affecting the cost of repair (Table 4). Because of the 'product development' layer, the indicators 'Amount of Restricted Materials (REACH) in products' and 'Amount of Prohibited Materials (SVHC) in products' have been selected to understand whether any carpet contains these materials, so they can be eliminated to reduce health risks and facilitate recycling at the end of life (so moved to the CE configuration 4). Interestingly, the indicators

‘Existence of Repair Manual with instructions‘ and ‘Availability of repair kit or spare parts’ have been found interesting and added to the list, because they may be important if the company decided to provide a similar type of a product to B2C market, where the customer could be encouraged to ‘repair’ carpets themselves.

Table 4. A final indicator set for CE configuration 3. * this indicator has been customized to address the particularity of the process.

Nr	Indicator name	CarpetCo comments
1	Existence of Repair Manual with instructions	Interesting indicator, which can be considered for the future. Making the manual available for the user is important to give the user "right to repair" and possibly encouraging the user to repair the product
2	Availability of repair kit or spare parts	Interesting indicator, which can be considered for the future. Repair kit and spare parts available for the user enable the user to repair the product when necessary. It may encourage the user to repair/replace the parts instead of disposing the whole product
3	Amount of Restricted Materials (REACH) in products	Important to reduce (or eliminate) hazardous/toxic material content in products to minimize health risks and increase potential for open loop recycling
4	Amount of Prohibited Materials (SVHC) in products	Important to reduce (or eliminate) hazardous/toxic material content in products to minimize health risks and increase potential for open loop recycling
5	Number of modules	Modular design facilitates repair, reuse, recycling and remanufacture.
6	Time for worn part replacement*	It's necessary that worn parts are easily accessible and visible, in order to facilitate and economize on the process of their replacement
7	Product Solid Waste Fraction	We need to measure how much product is 'saved' from removal due to our modular design and repair

For CE configuration 4, the question in focus was about what sustainability performance indicators should be measured when taking the product back for closed loop recycling, i.e. recycling the used carpet to be used as an input to produce same product type (therefore, the CE strategy ‘reduce impact in raw material and sourcing’ has been selected together with CE ‘recycle’). As a result, the final set of indicators consisted of eight indicators (Table 5), which mostly covered environmental aspects (indicators nr. 2 to nr. 8). The environmental indicators covered the ‘material’ aspects, thus providing an indication to what extent is the product in its current form suitable for recycling (indicators nr. 3, 4, 5 and 6), and what potential performance of the recycling process could be (indicators nr. 7 and 8). It is interesting to note that the initial indicator set proposes indicators that measure other aspects during recycling, such as ‘Hazardous Solid Waste Mass Fraction’, ‘Hazardous liquid Waste Mass Fraction’, ‘amount of water used for recycling’ and ‘amount of hazardous substances using for recycling’. These indicators would become key indicators if the case company would come from the electronic sector, where recycling of electronics often implies usage of great amounts of energy, water and acids to recover, for instance, rare elements from batteries (Zeng et al., 2014). Indicators nr. 3 and 4, on the other hand, could have been deselected by the company because of their intention to do a closed loop recycling; however, the company decided to make sure their product is free of the restricted materials to avoid contamination in case the recycling is done by another entity (open loop recycling). The indicator 'Take back cost' measures performance on operational costs of product take back system, while the indicator 'Load mode of transport' should provide an indication how much the space capacity of transport is used to transport used product for recycling, thus affecting the fuel consumption and cost of transportation.

Table 5. A final indicator set for CE configuration 4.

Nr	Indicator name	CarpetCo comments
1	Take back cost	This indicator is important to understand the costs associated with a product take back option. Take back collection requires reverse logistic in place
2	Load mode of transport	Important to understand how much the space capacity of transport is used to transport used product for recycling
3	Amount of Restricted Materials (REACH) in products	Important to reduce (or eliminate) hazardous/toxic material content in products to minimize health risks and increase potential for open loop recycling
4	Amount of Prohibited Materials (SVHC) in products	Important to reduce (or eliminate) hazardous/toxic material content in products to minimize health risks and increase potential for open loop recycling
5	Painted, Stained or Pigmented Surfaces	Current usage of glue complicates the separation for recycling
6	Number and type of material in a product	We need to make sure our materials are compatible for recycling
7	Recycled Embodied Energy	Maybe important but difficult to calculate. However, it may be important to measure energy necessary to recycle and produce one kg of the recycled material to be used as an input for our new carpet
8	Waste generated in the recycling process	This indicator measures the waste amount generated in the recycling process.

Figure 4. shows the number of indicators from all final sets per sustainability dimension, which gives an overview of how the dimensions are represented and what aspects are covered (some indicators are cross-dimensional).

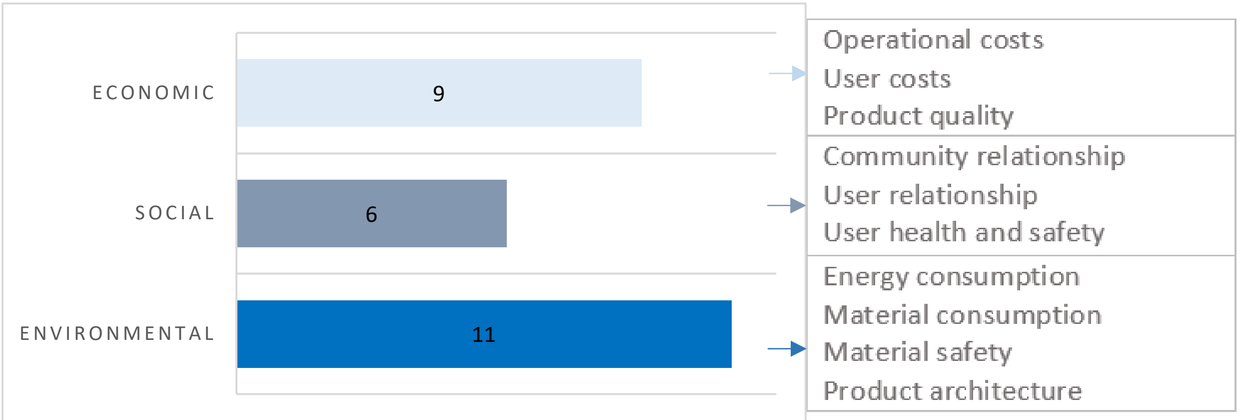

Figure 4. *Number of indicators per sustainability dimension and key aspects covered by selected indicators.*

The final overview of sustainability aspects to be measured by selected performance indicators provides a good understanding to the industrial practitioners about key aspects that are likely to be affected by the described CE initiative (combination of CE configurations). Therefore, this set acts as a proxy of what has to be measured in order to assess potential sustainability performance of the selected CE initiative, which can then be compared to the 'linear' initiative on the basis of the same set. Furthermore, the 'business process' dimension places focus not only on activities (i.e. what is performed or not), but on the interconnectedness of these activities (e.g. how a decision taken during business model development or product development can constrain or enable decisions at, for instance, end of life operations). In order to understand the sustainability performance of the selected CE initiative, the final indicator set has to be calculated (Figure 2, Step 3). For that, data has to be collected and calculated, as provided in the formula column in the corresponding 'Leading performance indicator database' (Section 2.1.). Furthermore, in order to understand the results of the calculated indicators for each CE configuration, it is necessary to collect same type of data for the baseline system, i.e. the current, non-CE, system. For instance, the indicator 'Product Solid Waste Fraction' from CE configuration 3 (Table 4) can help the company to understand whether any waste 'savings' occur because of the repair service; the indicator 'Number and type of material in a product' for CE configuration 4 would help the company to understand whether the current product or the redesigned product is compatible for recycling, if not, the CE strategy can be 'postponed' so the company could investigate materials to be used for the product in order to increase its recyclability (if desired). The responsibility for setting up a data collection plan could be placed on the sustainability or environmental manager, who then establishes a process of collecting data across departments and, by understanding the results of indicator calculation, can influence the decisions on CE implementation. For instance, if the indicator 'Cleaning agents used by service providers' (CE configuration 2) shows that a large portion of cleaning agents are used for carpet cleaning during cleaning services (which in that case would increase cost for CarpetCo spend on cleaning agents during service provision as a part of the PSS), then product development team can be involved to address the design (or choice of materials) to reduce the need for cleaning. These examples show how operating with indicators across business processes can facilitate learning about CE and highlight the importance of leading indicators as early-warning informants of potential consequences of decisions in a company. Furthermore, the dynamic process of indicator selection allows a company to select indicators relevant for its sector, product or process, thus increasing the certainty of operating with relevant indicators, as opposed to using a ‘prescribed’ set of indicators, which may not reflect the ‘reality’ of the company (for instance, the indicator ‘amount of conflict resources (e.g. tin, tungsten, gold) used in a product’ may be irrelevant for a company from textile sector, however maybe a very important indicator for an electronics company to ensure their usage of such resources does not come from a conflict zone that may perpetuate violence).

4. Conclusions

A growing body of the literature on CE continues to focus on developing support for manufacturing companies in their transition to CE, ranging from frameworks of CE strategies (EMF, 2013), to business model design (Pieroni et al., 2019) and product design (Moreno et al., 2016) for CE, as well as approaches to measuring performance of CE (Azevedo et al., 2017; Cayzer et al., 2017; Ellen MacArthur Foundation, 2015). Despite the growing evidence that transition to CE would require transformation of multiply organizational business process, there is a lack of tools that can support a manufacturing industry in identifying what has to be measured, how and where, so to support decision making for CE. Furthermore, the complexity is intensified, when companies would like to understand the sustainability performance of CE solutions, they are considering to implement. Studies highlight that ‘prescriptive’ measures, for instance, available from material flow analysis, or ‘prescriptive’ indicators such as ‘recyclability of the product’ may not be sufficient to address the complexity of CE configurations (Agrawal et al., 2012). In regard to increasing recyclability, Goldberg (Goldberg, 2017) raises concerns over circulating materials and products that contain toxic substances (e.g. mercury or brominated flame retardants), thus possessing a risk of perpetually creating and moving contamination in the system, if the materials are entering new cycle through recycling. This calls for creating a better understanding of uses of these toxic substances in products to minimize the risk of systemic exposure, but also to quantitatively assess any CE strategy on its potential sustainability contribution prior its implementation. Quantitative assessments may also support manufacturing companies in realizing the objectives of the EPR legislation.

This study focused on presenting the final indicator set, which can be used to measure the potential sustainability performance of CE initiatives in a manufacturing context. For this, a case company example was set up to show how the selected tools, the indicator database and the indicator selection procedure, developed in earlier studies and described in (Kravchenko et al., 2019; Kravchenko et al, 2019a, in review for JCLP), have been utilized. By taking a case example, we demonstrated i) the importance of operating with indicators across business processes; and ii) the importance of a dynamic indicator set (as opposed to the ‘prescribed’ indicators). Based on the final performance indicator set relevant for the case, the decision can be made to either implement the strategy, select/combine with another or avoid the implementation altogether.

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