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1 Application of Value Stream Mapping tool to Improve Circular 2 Systems.

3 Maria Victoria Hernandez Marquina^a*, Peggy Zwolinski^a, Fabien Mangione^a

4 ^aUniv. Grenoble Alpes, CNRS, Laboratoire G-SCOP, 38000 Grenoble, France

5 * Corresponding author. E-mail address: maria-victoria.hernandez-marquina@grenoble-inp.fr

6 **Abstract**

7 Circular Economy is a model that proposes the closure of loops in the production of goods and services to
8 reduce the depletion of natural resources, pollution, and high levels of production. On the other hand, Lean
9 Manufacturing, is a philosophy that focuses on the development of productivity through the elimination of
10 waste and the increase of value. This article explores the integration of lean manufacturing concepts and
11 tools in a circular context. First, a literature review is presented on the common concepts of waste and
12 value, the circular economy model and the indicators developed previously in the literature. Subsequently,
13 the adaptation of the Value Stream Mapping (VSM) is presented, with the integration of a set of indicators
14 proposed related to the concepts of circularity and longevity. Finally, the application of this tool is
15 presented through a case study, which proves that circular systems can be represented and evaluated with
16 the adaptation of Lean tools.

17 **Keywords**

18 Circular Economy, Lean Manufacturing, Key Performance Indicators, Value Stream Mapping.

1. Introduction

The Circular Economy was born as a new economic model to overcome the problems related to the depletion of natural resources and the environmental crisis, due to the growing consumption of products and services. This demonstrates the importance of changing the classical consumption model, usually related to a linear supply chain (take-make-dispose). Therefore circular economy is based on rethinking and redesigning products and services, implementing the recirculation of materials, in order to regenerate natural systems and reduce the generation of pollution and waste (EMF-Ellen MacArthur Foundation, 2013).

Although in recent years, there has been an increase in research to understand its implementation and consequences. This economic model represents a challenge due to the existing barriers between the theories developed by the academy and those of the practitioners (Nadeem et al., 2019). Indeed its broad concept linked to sustainability makes it difficult to implement and evaluate it in the development of efficient practices (Geissdoerfer et al., 2017).

For the deployment of competitive and efficient production systems, it is necessary to implement mechanisms to measure and improve their performance. To this end, the Lean Manufacturing philosophy developed in the Toyota Production System proposes various tools to achieve this goal, focusing on time reduction through the elimination of non-value-added activities (Womack and Jones, 1996).

On the one hand, Circular Economy seeks a better use of resources to solve problems related to shortage of raw materials and environmental issues through the closure of loops. On the other hand, the Lean philosophy seeks to eliminate waste to create value and thus obtain more efficient systems (Nadeem et al., 2019). Therefore, the concepts of Circular Economy and Lean Manufacturing pose different meanings of value and waste, which in turn could complement each other, bringing great benefits to the development of the manufacturing sector.

In accordance with the above ideas, the question "How Lean approaches could represent and evaluate circular systems?" is posed. Subsequently, the evidence collected to establish the relationship between the Circular Economy and the Lean Manufacturing is reviewed. Afterwards, the adaptation of the Value Stream Mapping (VSM) is introduced to represent, evaluate and improve a circular production system. In addition, a group of indicators based on the concepts of circularity and longevity (Figge et al., 2018) is proposed to be integrated into the VSM.

This research is structured as follows. A literature review is presented in section 2 to explain the process that was carried out to determine the gap under study, the background and main associated concepts, as well as the methodology to be followed to answer the research question posed above. Section 3 describes the adaptation of the VSM to a circular system, which, for the purposes of this article will be referred to as circular VSM, and the integration of a proposal of indicators for the measurement of longevity and circularity. Section 4 corresponds to the validation of the hypothesis through the circular VSM. In section 5, the application of the proposal through a case study is showed, and finally, in section 6 the discussion and the conclusions are presented.

2. Literature Review

2.1. Methodology

This research is based on four phases, corresponding to (1) a review of the literature to define the scope and hypothesis of the research, and understand the relationship between Circular Economy and Lean Manufacturing. (2) the adaptation of the VSM to represent and evaluate circular systems with the integration of new indicators. (3) the validation of the circular VSM. and finally, (4) the application of this tool in a case study.

A literature review was conducted in February 2020 to find the common concepts and possible divergences between Lean philosophy and Circular Economy. At this stage three database (Science direct, Web of Science and Google Scholar) were used to find academic publications related to the research terms “Circular Economy”, “Reverse Logistic”, “Lean Manufacturing”, “Lean Tools”, “Barriers in Circular Economy”, “Circular Economy Indicators”, “Sustainability” and their possible combinations. The search included title, abstract and keywords and was limited to works published within the past 10 years.

Subsequently, according to the information contained in the abstracts, 56 articles were selected, which were classified into 8 main groups corresponding to: Circular Economy Concept, Closed Loops and Reverse Logistics, Indicators in Circular Economy, Industrial Symbiosis, Lean and Circular Economy, Lean-Green-Sustainability, Lean tools, and Value and Barriers in Circular Economy. In this research the selection of the articles was based on the following criteria of relevance:

- Contribution to the definitions of the two main theories (Circular Economy and Lean Manufacturing).
- Possible combination of both theories in the same literature.
- Identification of concepts in common between the two theories.
- Barriers in the implementation of circular systems.
- Measurement of the Circular Economy.

Circular Economy and Lean Manufacturing are theories frequently used in the research of the last years, however, to refer to their fundamental concepts, there is a group of authors that is continuously named in the literature. By the part of the Circular Economy, Webster (Webster, 2013) and Ellen MacArthur Foundation (EMF-Ellen MacArthur Foundation, 2013) guide the principles of this model. While in the case of Lean Manufacturing, the main precursor of the Toyota Production System is Taiichi Ohno (Ohno, 1988), and the authors Womack and Jones (Womack and Jones, 1996) who define the principles and tools of this philosophy.

2.2. State of the art

2.2.1. Waste and value

In the analysis of the literature it was observed that Circular Economy and Lean Manufacturing have been combined for the elaboration of conceptual frameworks at a strategic level and they have in common the terms of waste and value. Nadeem et al. 2019, combined both concepts under the Lean philosophy and the Circular Economy, giving as a result:

Value “Any activity/output that utilizes its required resources in a manner that maximizes its utility at all stages of its lifecycle including the afterlife, as well as to ensure the longevity of its lifecycle while satisfying the needs/demands of the stakeholders (People [present and future] and Planet) and making impact for them.”

Waste “Any activity that leads to the harmful outputs for the stakeholders (People [present and future] and Planet) and does not incorporate the sustainability of the two in long-term, is a wasteful activity.” **In other words, it defines any activity that negatively affects the development of people and the planet in a sustainable way.**

2.2.2. Boundaries of the Circular Economy Concept

Previous research has associated the Lean Philosophy as a means to apply the Circular Economy, and they have developed conceptual frameworks for its implementation (Nadeem et al., 2019). It was also noted that in the literature have been integrated these two areas with the product-services system (PSS) model (González Chávez et al., 2019) (Romero and Rossi, 2017). However, these works have focused on the strategic aspect of the organizations.

Following this order of ideas, a question arises about the management of operations in circular environments. Since the fact of closing the loops and the low certainty about procurement due to the recirculation of materials puts in evidence the integration of new operations (Korhonen et al., 2018). Consequently, new waste in terms of Lean philosophy and Circular Economy could be generated. Thus, the process of procurement represents a challenge in the implementation of Circular Economy, which led to the definition of a first statement:

- a) The re-entry of the material into the production process could represent low certainty in the quantity, quality, and variety of the procurement. (Tura et al., 2019) (Hart et al., 2019) (Singh and Ordoñez, 2016) (Brissaud and Zwolinski, 2017).

With this first statement it was determined that this low certainty in procurement is associated with an operational level, for this reason, a second statement arose:

- b) It is necessary to add new operations for the recovery and restoration of the material in the closing of the loops such as transport, classification, inspections, cleaning, and disassembling. (United States International Trade Commission, 2013) (Nee et al., 2013) .

In order to define the circular economy concept, we took as a starting point the three principles defined by Ellen MacArthur Foundation, 2013: (a) rethink and redesign products and services, (b) keep products and materials in use, and (c) regenerate natural systems. Then, with the ultimate goal of study the impact of managing operations under a circular and Lean approach, it was decided to limit this concept to the second principle which is closely related to recirculation and material flow.

2.2.3. Circular Metrics

Several authors have elaborated tools and indicators to measure the performance of circular systems, proposing evaluations for different scopes (micro, meso and macro level) (Kristensen and Mosgaard, 2020), and for different stages of the product life cycle (design, manufacturing, consumption, disposal, end-of-life) (Mesa et al., 2018) (Huysman et al., 2017) (Corona et al., 2019).

According to the concepts of this economic model, the main dimensions evaluated are associated with principles of sustainability (Corona et al., 2019), such as economic, societal and environmental performance, and the addition of a new parameters related with the loops closure. Due to the fact that the Lean tool selected for this study already took into account sustainability metrics in the Sustainable VSM presented by Brown et al., 2014, it was decided to go deeper into the metrics related to circularity.

To evaluate the performance of circular systems, several authors agree that the way to do it is through circularity ("number of times a resource is used in a product system") and longevity ("the length of time that a resource is used") (Figge et al., 2018). These are related to the permanence of the product in loops within the same production system and the time linked to this permanence (Franklin-Johnson et al., 2016). For this reason, these two concepts are considered to measure the performance of the circular system under study.

2.3. Hypothesis

Based on the literature review, the statements described above and the research question "How Lean approaches could represent and evaluate circular systems?", a hypothesis was established:

Lean Manufacturing highlights the waste produced in a circular industrial system, which allows its subsequent improvement.

3. Adaptation of the VSM Tool for Circular Systems

To test the hypothesis described in section 2.3 and to answer the research question "How Lean approaches could represent and evaluate circular systems?", the adaptation of the VSM in a circular environment is

135 proposed, since it is a Lean tool that allows a global vision of the system's interactions and also highlights
136 the generation of waste (Kuhlang et al., 2011).

137 As a proposal, a Circular VSM is designed which establishes the evaluation criteria for circular systems,
138 considering the concepts of value and waste (Nadeem et al., 2019). Hence an overview of the supply chain
139 and its interactions, as well as the material flow, can be obtained. At this phase the aspects to be evaluated
140 are divided into four main groups (Faulkner and Badurdeen, 2014) (Figge et al., 2018): (a) economic
141 metrics, (b) environmental metrics, (c) social metrics and (d) circular metrics, and a series of indicators were
142 established according to each metric, which are shown in Table 1.

143 **Table 1.** Metrics and indicators of Circular VSM

Economic metrics	Environmental metrics	Social Metrics	Circular metrics
Lead Time	Energy, water, and material consumption.	Physical work, level of noise and work environment.	Circularity and longevity.

144

145 *3.1. Proposition of circular indicators*

146 As expressed in the background, many authors have proposed metrics related to the circular economy and
147 the concepts of longevity and circularity, but when trying to integrate them to the VSM tool under its initial
148 conception, these metrics become complex to be represented in the mapping.

149 Based on the concepts of circularity and longevity defined by Figge et al., 2018, a series of indicators is
150 developed to be integrated into the VSM. **These indicators are proposed under a modular vision of the final
151 product. Because at the end of its useful life, it allows its later disassembly in components that can be
152 integrated again in the production process of the same final product through loop closures such as
153 remanufacturing or refurbishment.**

154 *3.1.1. Circularity Indicator*

155 From the modular vision of the product, we propose the calculation of a weighted average circularity,
156 which is based on the number of times each component/product is used in a circular system (cycles).

157 For the development of the calculations shown below, it is proposed in a first time, the calculation of the
158 average circularity by type of component, in other words, the average circularity for each component that is
159 integrated in the final product. In a second time, the average circularity of a finished product assembled
160 from several components is proposed.

161 This first indicator of circularity per component showed in equation (1) is the weighted average of the
162 respective number of cycles (d_i = number of cycles type i) with the number of components (q_i = quantity of
163 components with the number of cycles type i). n represents the total number of cycle groups.

$$164 \quad \text{Circularity of the component (cc)} = \frac{\sum_{i=1}^n q_i * d_i}{\sum_{i=1}^n q_i}. \quad (1)$$

165 To explain the application of this equation we take the following example: suppose that the production
166 process gives as a final result a Product (D). As an input, there are 3 components (A, B, C) which are
167 assembled in the process to give D as a result.

168 To know the circularity of each incoming component (A, B, C), it is necessary to apply equation 1, for which
169 it is required to know the number of cycles associated with each incoming component.

170 Table 2 shows the data that will be considered for the calculation, which are the quantity of components
171 for each class (A, B, C) and their respective number of cycles in the input inventory and the result of the

172 circularity of each component. In the case of a new component, the number of cycles (d_i) is equal to 0, since
 173 this element is virgin and has not been used previously in another product.

174 **Table 2.** Data for the calculation of the circularity and their result per component

Type of Component	Number of cycles (d_i)	Quantity of components with the number of cycles type i (q_i)	Circularity of the component (cc)
A	0 (new components)	10	3,53 Cycles
	2	20	
	4	30	
	7	15	
B	0 (new components)	12	3,11 Cycles
	1	7	
	5	20	
	6	5	
C	0 (new components)	11	2,35 Cycles
	2	12	
	3	8	
	4	15	

175

176 Through the previous example, a different circularity is calculated for each type of component, and in turn
 177 it is observed that for each type of component there are different subgroups according to the number of
 178 cycles, these subgroups represent n according to equation (1).

179 In the case of the assembly of the final product the circularity will be calculated as the weighted average of
 180 the circularity of each component (cc_j = Circularity of the component j) with the quantity of this component
 181 in the final product (qc_j =Quantity of components j used in the final product). m represents the total
 182 number of component types, according to the equation (2). The unit of measurement of circularity is the
 183 number of cycles per unit (component or final product).

184
$$\text{Circularity of the final product (cp)} = \frac{\sum_{j=1}^m cc_j * qc_j}{\sum_{j=1}^m qc_j} . \quad (2)$$

185 Continuing with the previous example, table 3 shows the data necessary for the calculation of the
 186 circularity of the final product, as well as its respective value, after applying equation (2).

187 **Table 3.** Data for the calculation of the circularity and their result per final product.

Type of Component	Quantity of components used in the final product (qc_j)	Circularity of the component (cc_j)	Circularity of the final product (cp)
A	2	3,53	2,80 cycles
B	1	3,11	
C	4	2,35	

188

189 This circularity of the final product means that D at the end of the production process on average has
 190 performed 2,80 cycles, i.e. the final product carries the closure of almost three loops. This makes it clear
 191 that as the products circulate in the system and the cycles increase, the circularity increases.

192 3.1.2. Longevity Indicator

193 From the modular vision of the product, we propose the calculation of a weighted average longevity, which
 194 is based on the age that each component has in a circular system.

195 For the development of the calculations shown below, it is proposed in a first time, the calculation of the
 196 average longevity by type of component in the operations of the production process. In a second time, it is
 197 proposed another equation to obtain the average longevity of a finished product, which is assembled from
 198 several components.

199 This first indicator of longevity per component showed in equation (3) is the weighted average of the
 200 respective age (l_i = Age type i of the component) with the number of components (q'_i = Quantity of
 201 components with the age type i). n represents the total number of groups of ages.

202
$$\text{Longevity of the component } (lc) = \frac{\sum_{i=1}^n q'_i * l_i}{\sum_{i=1}^n q'_i} . \quad (3)$$

203 To explain the application of this equation, we continue with the example mentioned above, table 4 shows
 204 the data necessary for the calculation of longevity and its respective result by component.

205 **Table 4.** Data for the calculation of the longevity and their result per component

Type of Component	Age of the component (l_i) (years)	Quantity of components with the age type i (q'_i)	Longevity of the component (lc)
A	0 (new components)	15	3,87 years
	3	15	
	5	25	
	6	20	
B	0 (new components)	15	1,48 years
	1	7	
	2	15	
	4	7	
C	0 (new components)	16	1,74 years
	2	10	
	2	10	
	4	10	

206

207 Through the previous example, a different longevity is calculated for each type of component, and in turn it
 208 is observed that for each type of component (A, B, C) there are different subgroups according to the ages.
 209 These subgroups represent n according to equation (3). **In the case of a new component, the age of the**
 210 **component (l_i) is equal to 0, since this element is virgin and has not been used previously in another**
 211 **product.**

212 In the case of the assembly of the final product the longevity will be calculated as the weighted average of
 213 the longevity of each component (lc_j = Longevity of the component j) with the quantity of this component
 214 in the final product (qc_j = quantity of components j used in the final product). m represents the total
 215 number of component types, according to the equation (4).

216
$$\text{Longevity of the final product } (lp) = \frac{\sum_{j=1}^m lc_j * qc_j}{\sum_{j=1}^m qc_j} . \quad (4)$$

217 Continuing with the previous example, table 5 shows the data necessary for the calculation of the longevity
 218 of the final product, as well as its respective value, after applying equation (4).

219 **Table 5.** Data for the calculation of the longevity and their result per final product.

Type of Component	Quantity of components	Longevity of the component	Longevity of the
-------------------	------------------------	----------------------------	------------------

Component	used in the final product (q_c)	final product (l_p)
A	2	3,87 years
B	1	1,48 years
C	4	1,74 years

220

221 This longevity of the final product means that D at the end of the production process on average has a
 222 longevity of 2.31 years. This makes it clear that as the products circulate in the system and the age increase,
 223 the longevity increases.

224 Thus, proving that through the proposed indicators of circularity and longevity it is possible to evaluate
 225 loop closures and the permanence of resources in the system under study.

226 *3.2. Proposition to represent a circular supply chain through the VSM*

227

228 *3.2.1. Loop closures*

229 In the case of this research, two possibilities were considered for closing the loops through the
 230 remanufacturing process and through the refurbishing process. As a starting point we have the concept of
 231 remanufacturing, which according to Turki et al. 2017 is defined as “an industrial process in which used
 232 end-of-life products are restored to “like-new” conditions”. On the other hand, as far as the concept of
 233 refurbishment is concerned, there is not such a clear definition, in the case of Ellen MacArthur Foundation
 234 2019, they use the term of Refurbishing product “...synonymously with remanufacture and reconditioning
 235 as these terms are used interchangeably depending on the product group”. In this work, the concept of
 236 refurbishment is defined as renewing and restoring a product for later reuse.

237 In this particular case, the difference between the process of remanufacturing and refurbishment is that
 238 the first is a process that involves a transformation of the product to be integrated into the linear supply
 239 chain (linear process), to subsequently obtain new products. While the second, is related to a
 240 reconditioning process that is carried out completely parallel to the linear supply chain. It is important to
 241 note that both processes will result in "new" products that serve the same market. Figure 1 shows an
 242 illustration of these processes through the original icons of a VSM.

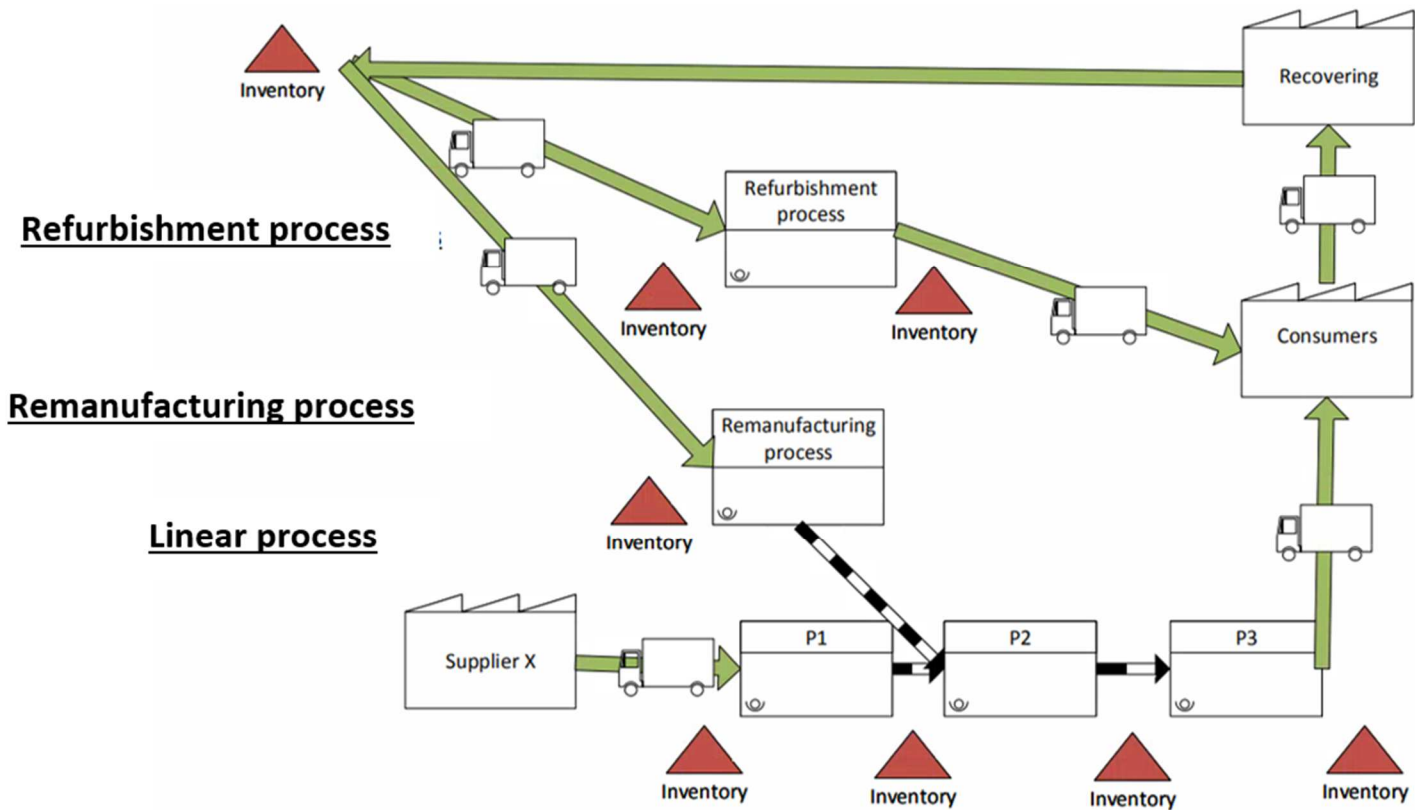


Figure 1. Representation of the refurbishment and remanufacturing processes in the VSM

3.2.2. Set of linear models

Since the uncertainty of procurement in the loops closures (Tura et al., 2019) (Hart et al., 2019) (Singh and Ordoñez, 2016) (Brissaud and Zwolinski, 2017), and the uncertainty of consumer behavior (Kirchherr et al., 2018), do not allow establishing a fixed rate of return of the product at the end of its useful life. Then the recovering process and the entry of material to these processes can be represented through companies that market used products (Suppliers of refurbishment and remanufacturing processes). In consequence, the production process consisting of a conventional linear process and two loop closures represented by the remanufacturing and refurbishment processes, are illustrated as a set of linear processes, as shown in Figure 2.

The fact of representing the circular system under a set of linear systems is valid, because the loop closure is being represented through the integration of circularity and longevity indicators in the VSM.

Refurbishment process

Remanufacturing process

Linear process

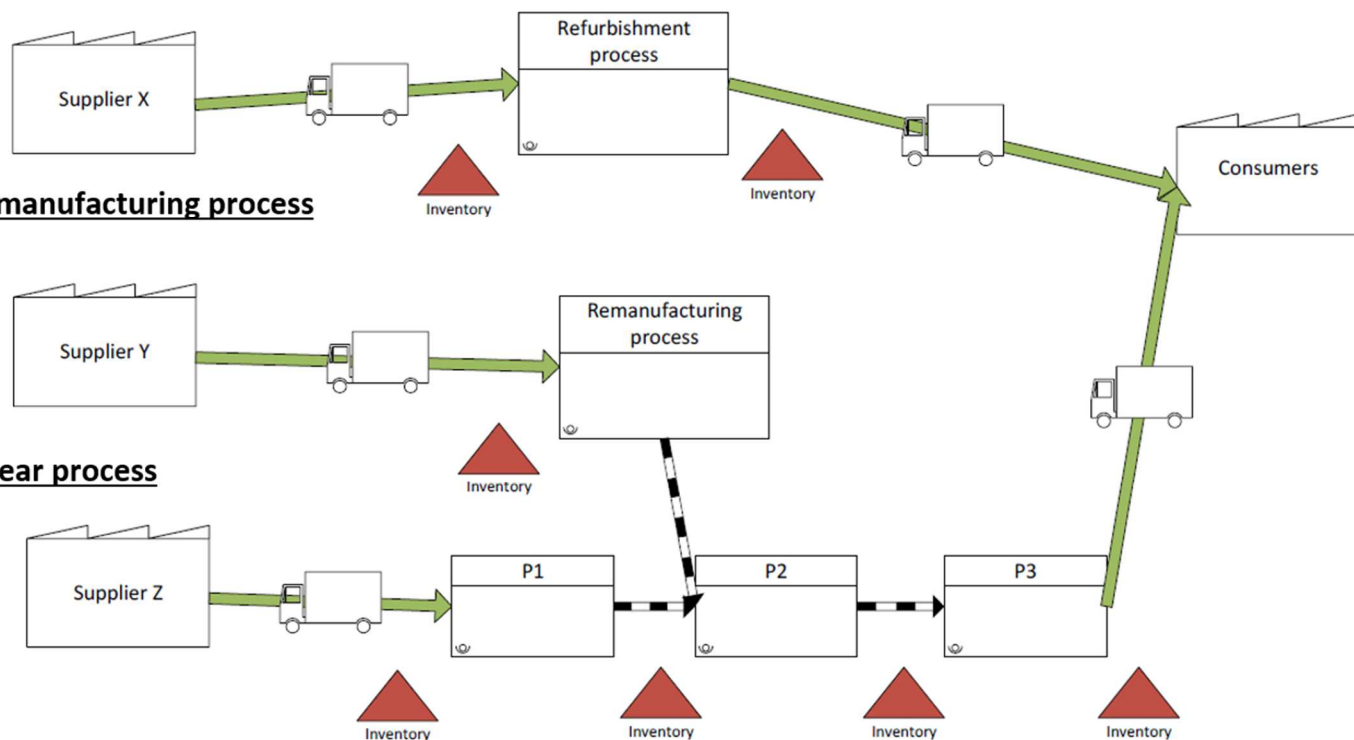


Figure 2. Representation of the refurbishment and remanufacturing processes in the VSM through a set of linear systems.

3.3. Economic, environmental, social and circular dimensions in the Circular VSM

According to the principles of circular economy presented above, the measurement of four main dimensions (economy, environment, society and circularity) is necessary to the evaluation of circular systems, which in this paper will be denominated circular performance. For this reason, it is shown below how each of these dimensions is represented and evaluated through the VSM.

3.3.1. Economic dimension

This dimension is represented by the timeline (Figure 3), which is one of the main indicators of an original VSM. In this line is observed the total time that takes the product from its arrival to the production process until it is delivered to the final customer. In turn in this line it is possible to observe the individual times of each process, and at the end it is observed the time that added value and the total time of the process (Lead time).

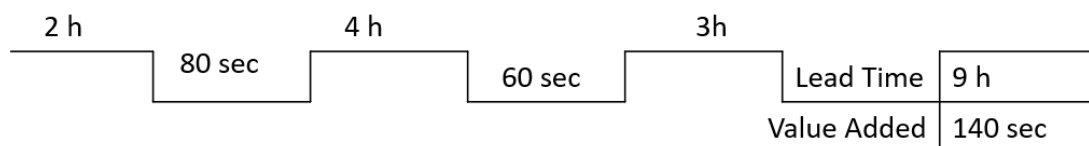
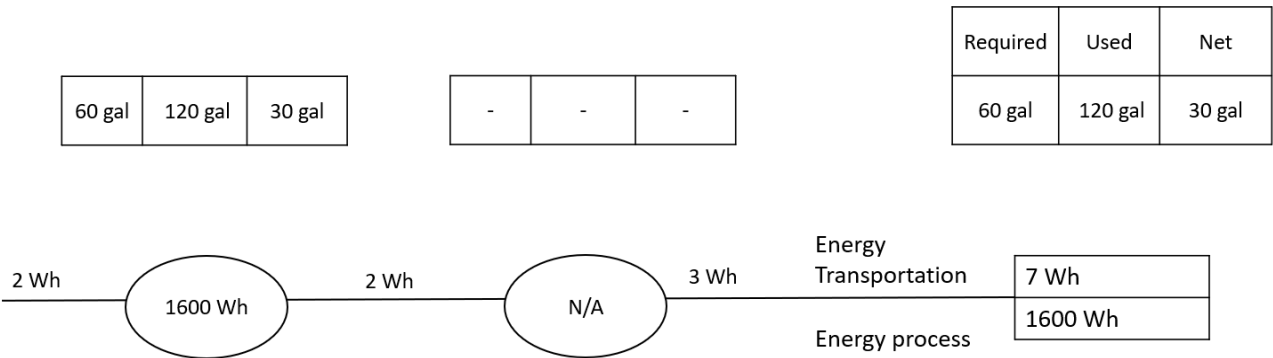


Figure 3. Timeline of the VSM

3.3.2. Environmental dimension

The environmental dimension is represented by the symbols parallel to the timeline, which represent water required (per specifications), used (actual), and net (lost) and energy (transportation and process) consumption (Figure 4). These representations were previously developed by Faulkner and Badurdeen

278 2014 in the Sustainable VSM. In addition, informative tables show the percentages of material used and
279 wasted below the process symbols.



280

281

282 **Figure 4.** water and energy consumption in the VSM

283

284 **3.3.3. Social dimension**

285 The social dimension is quantified through the indexes of physical work and work environment, which were
286 developed in the sustainable VSM established by Faulkner and Badurdeen 2014.

287 The Physical Load Index (PLI), is a measure determined through the answers of a questionnaire, which
288 considers the frequency of occurrence of different body positions and the handling of various loads. In the
289 development of the sustainable VSM (Faulkner and Badurdeen 2014), the authors suggest including the
290 maximum and average value for each work station. This value ranges from 0 to 56.

291 The second social metric included on the Sustainable VSM by Faulkner and Badurdeen 2014, measures the
292 work environment. This metric cover four risk types: Electrical Systems (E), Hazardous Chemicals/ Materials
293 Used (H), Pressurized Systems (P), and High-Speed Components (S). These are evaluated on a scale of 0 to
294 5, where 0 means that there is no risk and 5 means that there is a risk that has a high impact of damage and
295 high probability of occurrence. In addition, the noise level is also included in the information table of each
296 process.

297 Figure 5 shows the integration of these indicators in the VSM representation. The upper part shows the
298 metric of the work environment, in which each of its quadrants represents the 4 types of risk described
299 above. In this particular case there is no risk from electrical systems, nor hazardous chemicals or materials.
300 On the contrary, there are risks associated with pressurized systems and high-speed components, which
301 have an evaluation of 2, suggesting that there are risks with low impact and high probability of occurrence,
302 or high impact with low probability of occurrence.

303 In the case of the physical work metric (PLI), it shows the average value corresponding to 21.2 and the
304 maximum (worst) value that can be reached in this work process corresponds to 34.3. Finally, the noise
305 level corresponding to that workstation is shown, which in this example is 89 dbA.

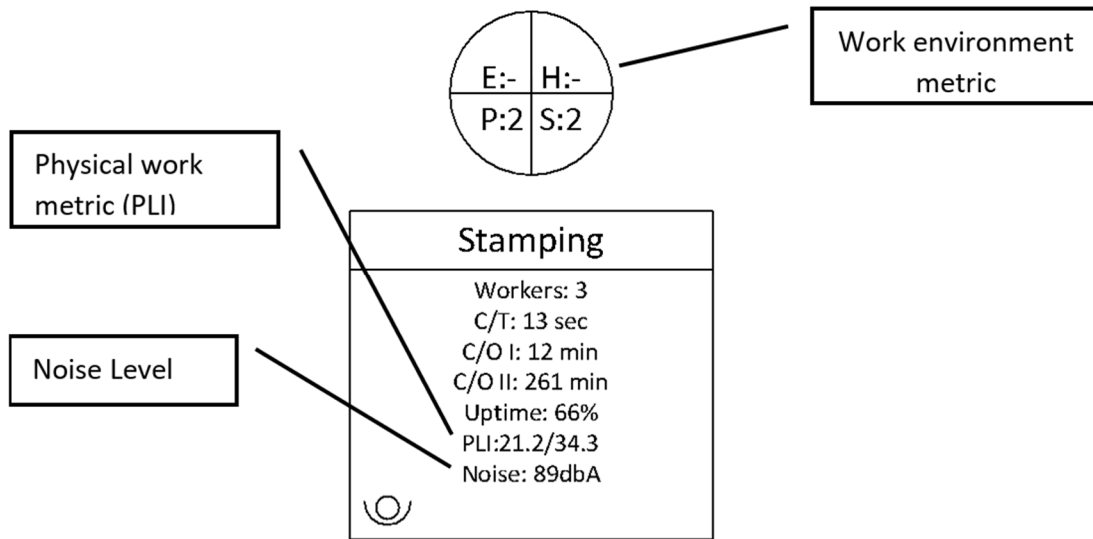


Figure 5. Integration of social metrics in the VSM [Faulkner and Badurdeen 2014].

3.3.4. Circular dimension

To complement our proposal and to be able to represent a circular system through the VSM, the indicators of longevity and circularity presented in section 3.1. are added to this type of mapping. For their representation, these new data were added to the figure of VSM inventories, as their measures are associated with the identity of each component or product and do not vary according to the transformation processes.

An example of this representation is shown in Figure 6. Taking as reference the examples exposed in section 3.1. linked to the indicators of circularity and longevity, we have a final product D which is composed by the assembly of the components A, B and C. In this illustration, two processes P1 and P2 are shown, which have two associated inventories, represented by the red triangles. In turn, these inventories show the average units of components/product and their respective measures of circularity and longevity.

To determine these values, in the case of the components (A, B, C), equations 1 and 3 were used, which serve to determine the circularity and longevity of each component (results of table 2 and table 4). In the case of product D, equations 2 and 4 are used, which are associated with the assembly that results in the final product D (results of table 3 and table 5).

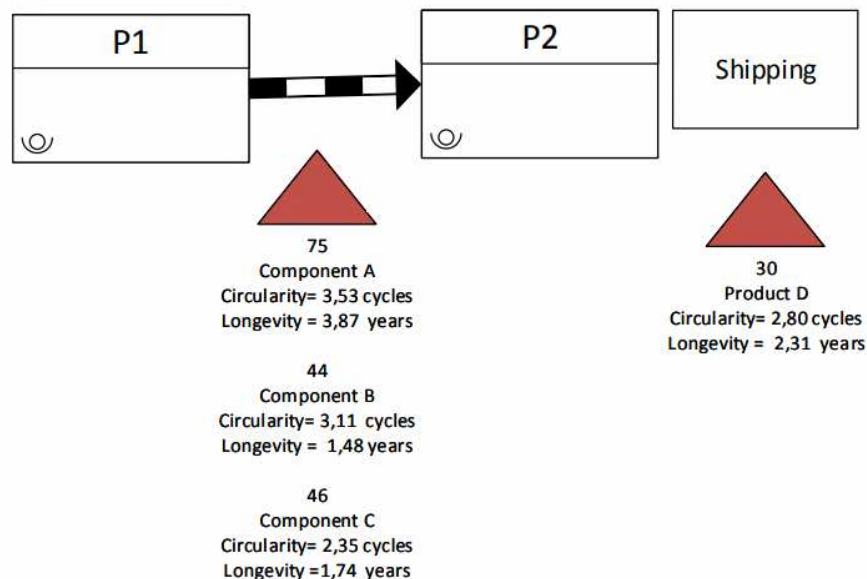


Figure 6. Representation of longevity and circularity indicators in the VSM.

According to the indicators and illustrations shown above, we prove that a circular system can be represented and evaluated through the VSM tool, thus answering our research question “How Lean approaches could represent and evaluate circular systems?”. Subsequently, through the information provided by these indicators, improvement points can be identified where the metrics do not show the appropriate values, considering the classic procedure of the application of the VSM. First, improvement points must be identified, and then appropriate solutions should be proposed to generate a new VSM to compare the current and proposed situation, with the ultimate goal of obtain significant improvements in the four dimensions of the circular performance.

3.4. Measurement of waste in the circular VSM

Considering the concept of waste described in the state of the art, it is observed that through the circular VSM several types of waste are put in evidence, which are listed below and linked to the mapping element to which they are associated. Under this approach it can be seen that the description of wastes is more extensive than for a conventional VSM, since more elements are considered as waste generators. Table 6, shows in a systematized way the VSM metrics associated to each waste and value.

- *Waiting times*: This type of waste is visible in the time line, through the inventory times, because through this it is visualized how long a piece waits to be processed in each process.
- *Inventory*: This type of waste is visualized through the average number of units waiting in the different inventories.
- *Over production*: This kind of waste can be determined through the comparison of the system's production and customer demand. In turn, this waste can be studied internally among the suppliers and internal customers of each process.
- *Defects and over-processing*: These types of waste can be studied through the information tables that provide the amount of material consumed and wasted, considering the causes of their origins. Also, complementary information that can help in the determination of these wastes can be found in the lines of water and energy consumption.
- *Transportation*: This waste is observable through the transport symbols and their duration in the timeline, as well as in the energy consumption through their illustration in the cartography.
- *Motion and unutilized talent*: These two types of waste are associated with the workers of the productive processes and their performance, which is why their appearance can be reflected in the social metrics, which allow us to have a vision of the work environment and the physical effort.

In addition, circularity and longevity are measures that support the "value creation", because according to the definition established in the state of the art, these two metrics allow to measure both the reintegration of goods to the productive processes, and the prolongation of its useful life.

Table 6. VSM metrics and each waste type and value.

Metrics	Wastes / Value							
	Waiting times	Inventory	over production	Defects	Over-Processing	Transportation	Motion	Unutilized Talent
Lead time	x	x			x			
Water consumption			x	x				
Energy consumption			x	x		x		
Social metrics							x	x
Material consumption			x	x				
Circularity								x
Longevity								x

4. Validation of the Hypothesis

The VSM has been adapted to integrate new processes (remanufacturing and refurbishment) to lead to the Circular VSM, which allows the representation and evaluation of circular production processes. Therefore, the necessary operations to close the loops (inspections, disassembles, cleaning, transportations, etc.) had to be included and will generate new waste in terms of Lean, as mentioned in the second statement, in section 2.2.2.

To illustrate this an example is provided (Figure 2). It can be seen that new processes are associated with new inventories, transports and movements that were not previously necessary in a linear supply chain. These new elements, are also related to the uncertainty characteristic of circular economy procurement, due to the diversity of incoming material in terms of quantity and quality, defined in the description of a first statement in the section 2.2.2. It is important to emphasize that under this model the linear supply chain is still necessary, since the other processes depend on it.

On the other hand, there are new production rhythms associated with the remanufacturing and refurbishment branches, which could generate overproduction and/or over processing. Finally, the development of these new processes could lead to defects in the products in process and/or finished products.

According to all previously mentioned, the hypothesis presented in section 2.3 "*Lean Manufacturing highlights the waste produced in a circular industrial system, which allows its subsequent improvement*" is validated. Because through the adaptation of this mapping, it is possible to identify improvement points (known as waste) in the circular supply chain and perform them through the method associated with a conventional VSM.

5. Application of the Circular VSM through a Case Study

A case study (Faulkner et al., 2012) was taken to validate the proposed Circular VSM. This case study was previously developed under a sustainable Lean approach, implementing the Value Stream Mapping (VSM) tool, and adding sustainable metrics to evaluate the economic, societal, and environmental performance of the system.

In the case of this research, it was decided to adapt this tool to show closed loops with remanufacturing and refurbishment processes, as well as the adaptation of circular metrics (circularity and longevity) to evaluate the performance of the system. To complete the data for the VSM, empirical information was collected, and then possible loop closure scenarios were raised and tested through a simulation software to complete the circular VSM case study.

The circular system is a hybrid system (linear and circular), in which circularity can be seen through two closed loops in the processes of remanufacturing and refurbishment. This circular system was conceived in a hybrid way. Indeed, in practice it is not possible to have a perfect circular system, so this model is proposed as an approach to a real productive system.

Figure 7 shows a global view of the case study represented in a VSM, while the details will be presented later on this paper. In this mapping (figure 7), it is exposed in the first stage the process of refurbishment, in the second stage the process of remanufacturing and in the third stage the linear process (linear supply chain) and its interactions for the fulfillment of the demand of the consumers.

Through the case study represented by the circular VSM, it can be observed that the four previously established dimensions of circular performance (economic, social, environmental and circular) are quantified through the indicators presented.

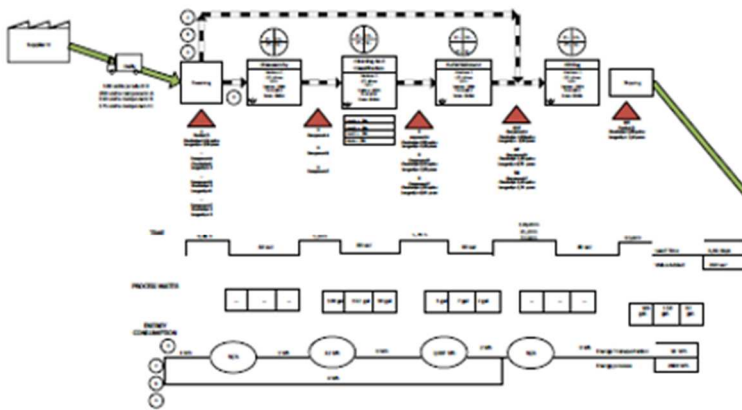
5.1. Material flow, circularity and longevity in the circular VSM

It is important to highlight that the VSM considers the flow of 4 different types of materials (components A, B, C and the final product D). These materials flow in three processes that are carried out in parallel with

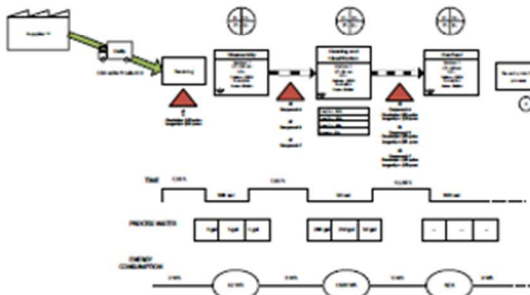
405 indicators of longevity and circularity respectively, through the information of the inventories. Figures 8, 9,
406 and 10 represent the set of linear processes belonging to refurbishment, remanufacturing and linear
407 process.

408 Figure 8 shows the beginning of the material flow in the refurbishment process, which starts with one
409 supplier, corresponding to the supply of used products D, component A, component B and component C.
410 Indeed, a refurbished product can be composed of used and new parts, and at the end of the process the
411 product is shipped directly to the consumer. In this process, it is observed that at the beginning, the
412 quantities in inventory of each type of product/component are shown with their respective indicators of
413 circularity and longevity. As these are used products of type D, the indicators show a circularity of 3.16
414 cycles and a longevity of 4.59 years, and in the case of components A, B and C, they have a circularity and
415 longevity of 0, because they are new.

Refurbishment process



Remanufacturing process



Linear process

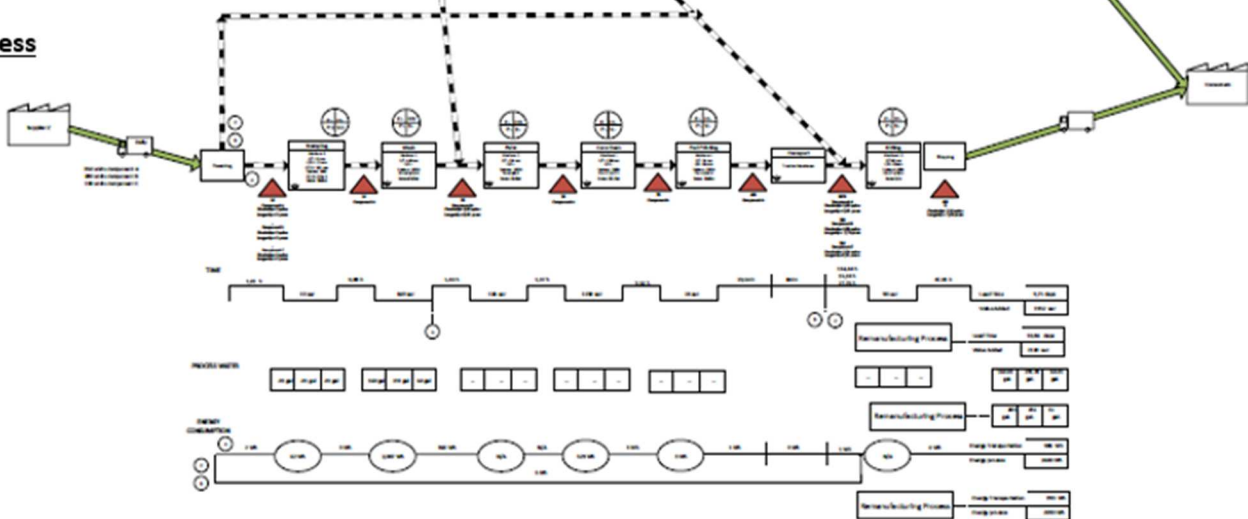
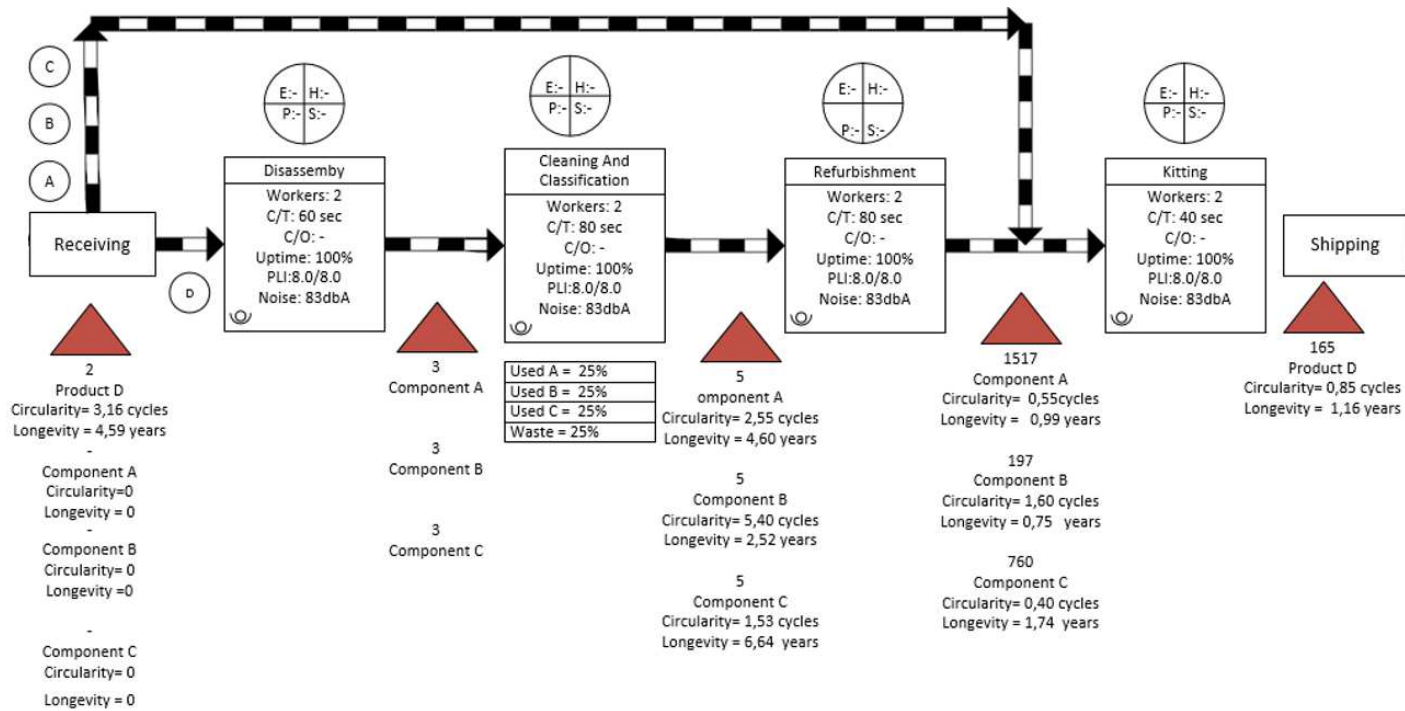


Figure 7. Circular VSM of case study

419

Subsequently, the inventory of the end of the refurbishment operation shows the new values of circularity (A= 0.55 B= 1.60 and C= 0.40 cycles) and longevity (A= 0.99 B= 0.75 and C= 1.74 years) of the components. This is due to the fact that after having gone through the disassembly, cleaning and classification and refurbishment operations, the flows of new and reused components converge to assemble the products D that will soon be shipped to customers, with a circularity of 0.85 cycles and a longevity of 1.16 years, which are shown in the shipping inventory. Below the cleaning and classification process, a table of percentages is shown. This corresponds to the portion of each type of component that continues in the production process and the percentage that becomes waste.



428

429

Figure 8. VSM – Refurbishment process

In the case of figure 9 (Remanufacturing process), there is one supplier of used products, for this reason, an initial inventory of product D with a circularity of 2.87 cycles and a longevity of 3.54 years is shown. Subsequently, before the overhaul operation, the circularity (A= 2.52 B= 1.55 and C= 4.55 cycles) and longevity (A= 1.52 B= 4.55 and C= 4.55 years) of each reused component are shown. And then these components are reintegrated into the linear process in two different flows, components A for painting operation and components B and C for the kitting operation. Also, Figure 9 shows the percentages of material used according to the cleaning and classification operation in a data table below the process icon.

437

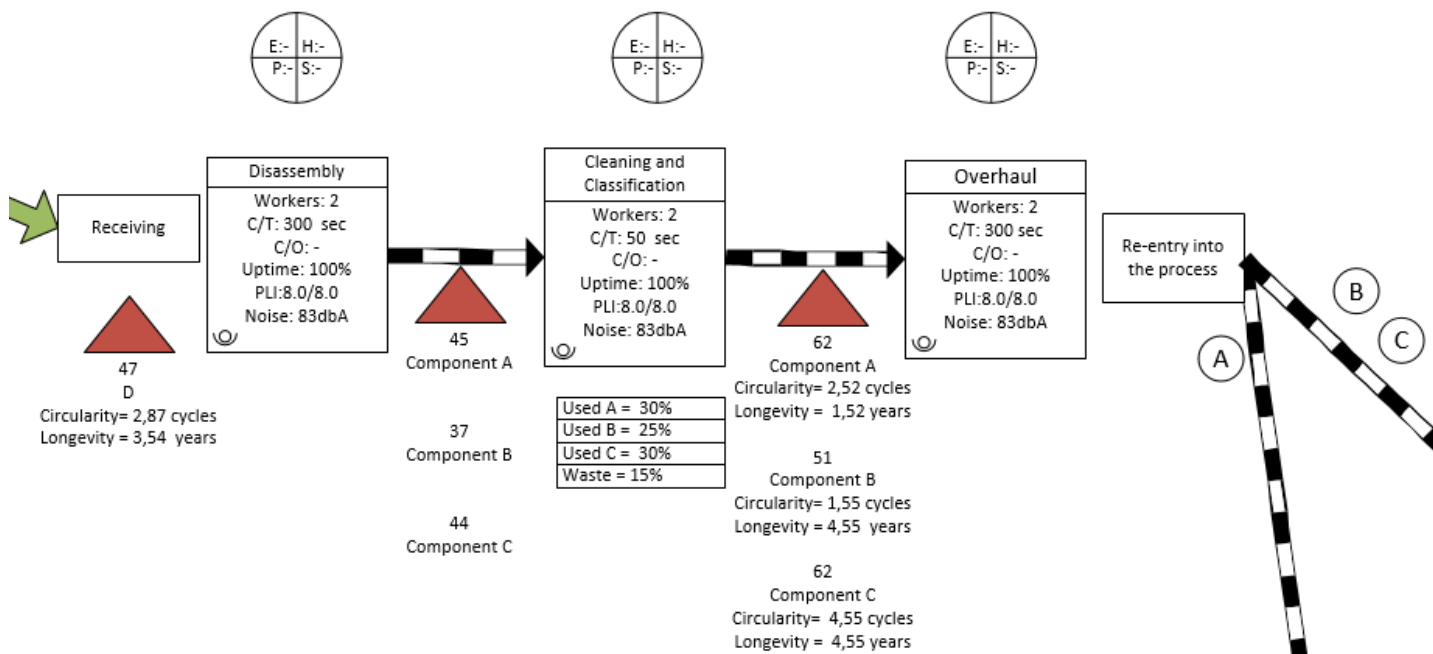


Figure 9. VSM – Remanufacturing process

Figure 10 shows the conventional linear process, with the supplier of new components at the beginning of the mapping, with a circularity and longevity of 0. And later, the entry of components types A from the remanufacturing process in the end of washing operation, which, when converging with the linear flow, has a circularity of 0,66 cycles and a longevity of 0,40 years. In the beginning of kitting operations, a new convergence with the remanufacturing process is shown through components B and C, which show a circularity (B= 0,59 and C= 2,24 cycles) and a longevity (B= 1,73 and C= 2,24 years) respectively. and finally, after assembly, there is the final product D with a circularity of 1,16 cycles and a longevity of 1,46 years.

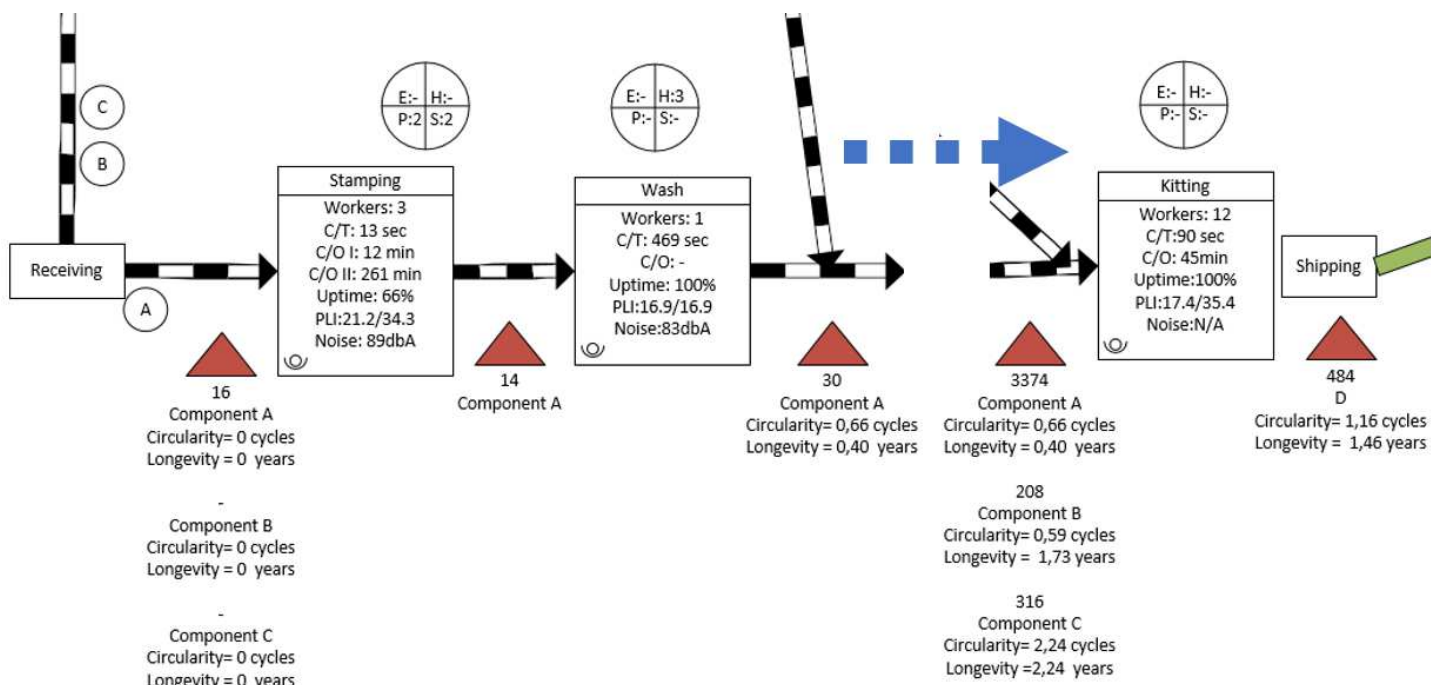
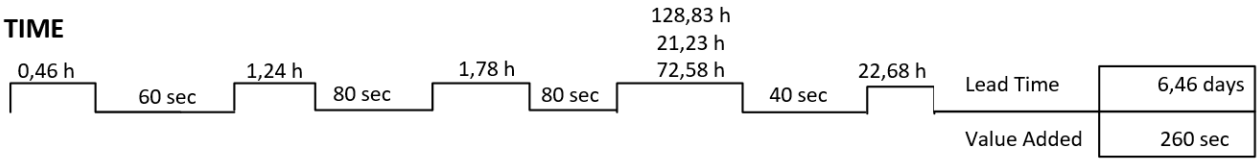


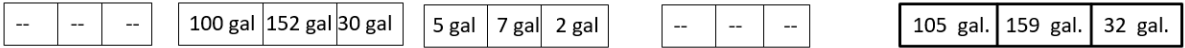
Figure 10. VSM – Linear process

5.2. Timeline, energy and water consumption in the circular VSM

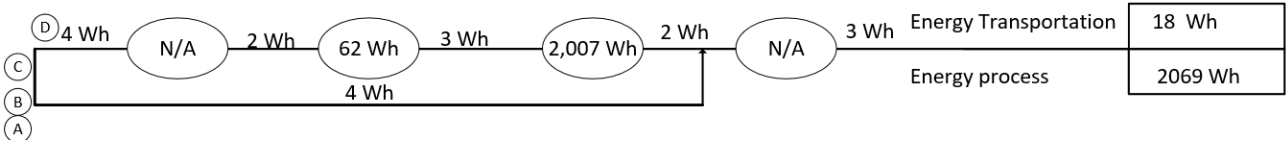
451 In the case of the refurbishment process, the material that enters through this process is sent to the
452 costumers, so the time line, water consumption and energy consumption are totalized directly after the
453 shipment in the same process (Figure 11). Otherwise is the remanufacturing process, because it is
454 integrated to the linear process, so it is observed that the process is cut through dotted lines (Figure 12), to
455 give entry to the material in the indicated points of the linear process.



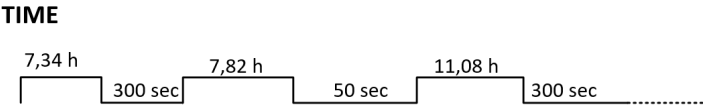
PROCESS WATER



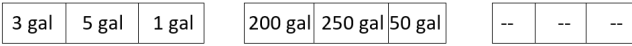
ENERGY CONSUMPTION



456
457 **Figure 11.** Timeline, energy and water consumption in the refurbishment process.



PROCESS WATER



ENERGY CONSUMPTION



458
459 **Figure 12.** Timeline, energy and water consumption in the remanufacturing process.

460
461 Figure 13 shows the time line, water consumption and energy consumption of the linear process, as well as
462 the convergence of these indicators with the remanufacturing process through the dotted lines. As in this
463 last process converge the linear production and the remanufacturing production, the final products are
464 assembled from mixed components of both processes. Therefore, at the end, in the totalization of the
465 indicators, we have the levels in which the time, water consumption and energy consumption of these
466 products vary. That means, the indicators of the continuation of the linear process show the consumption
467 of a product that is completely linear, while the totalization of the remanufacturing process shows the
468 consumption of a product that is completely remanufactured, that is why these values will be the limits in
469 which the real values of each finished product coming from these two processes fluctuate.

470

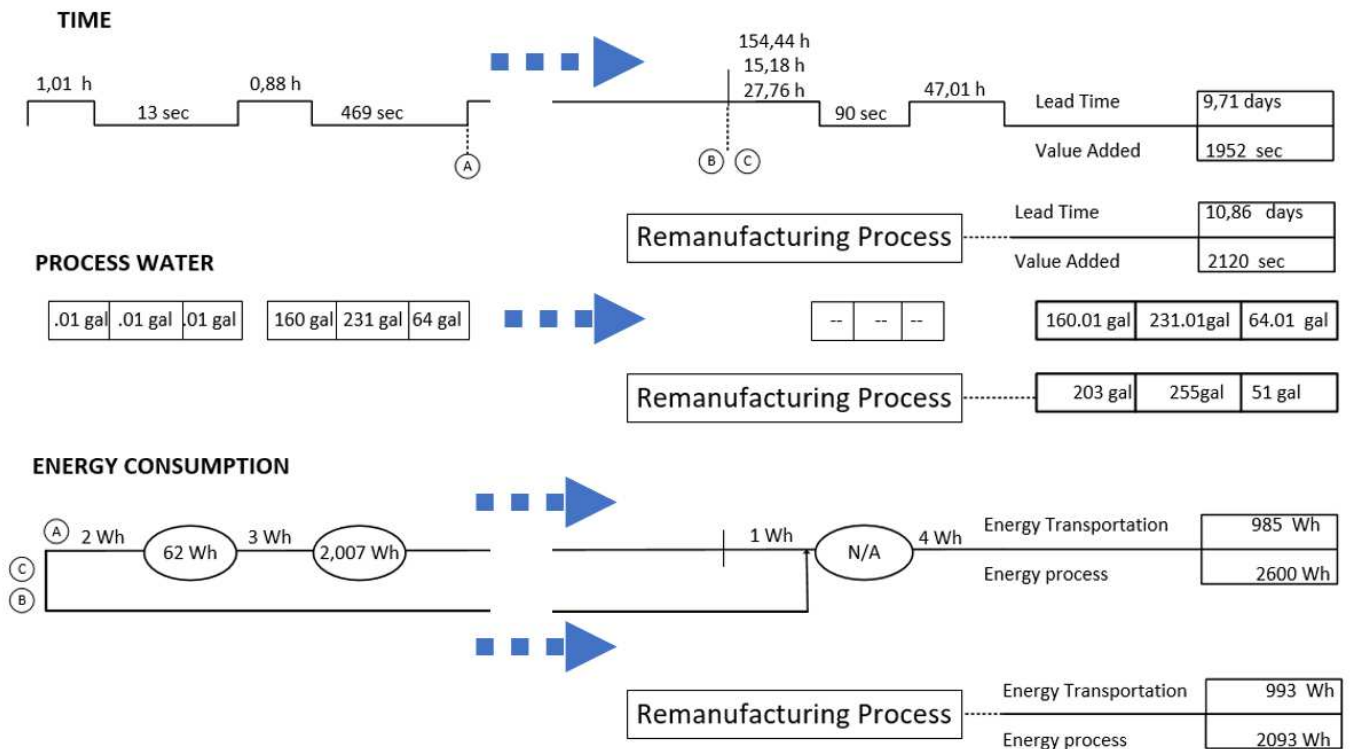


Figure 13. Timeline, energy and water consumption in the linear process.

5.3. Comparison of the indicators associated with a finished product D from each branch of the circular VSM

When comparing the performance of each branch of the circular process (Table 7), we can observe that in terms of lead time, the refurbishment process delivers the finished products in less time (6,46 days), followed by the linear process (9,71 days), and the remanufacturing process (10,86 days). With respect to water consumption, it is shown that the refurbishment process consumes less water (105 / 159 / 32 gal.), followed by the linear process (160,01 / 231,01 / 64,01gal.) and finally the remanufacturing process (203 / 255 / 51 gal.). With respect to energy consumption, it is shown that the refurbishment process has a better performance (18 / 2069 Wh), followed by the remanufacturing process (993 / 2093 Wh), and finally the linear process (985 / 2600 Wh). With respect to the circularity and longevity indicators, it is observed that only two aspects can be compared, due to the convergence of the remanufacturing process in the linear process, resulting that these two processes generate products with a higher circularity (1,16 cycles) and longevity (1,46 years) than the refurbishment process (0,85 cycles and 1,16 years).

With respect to the social metrics, in order to study their performance, it is necessary to carry out a specific review of each process, since it is not possible to make a general totalization that yields a value for the entire system.

Table 7. Comparison of the indicators associated with a finished product in the circular VSM

	Refurbishment process	Remanufacturing process	Linear process
Lead time (days)	6,46	10,86	9,71
Water consumption (gal.)	105 / 159 / 32	203 / 255 / 51	160,01 / 231,01 / 64,01
Required/ used/ net			
Energy consumption (Wh)	18 / 2069	993 / 2093	985 / 2600
Transportation / process			
Circularity (cycles)	0,85	1,16	
Longevity (years)	1,16	1,46	

490

491 This case study reaffirms that a circular industrial system can be represented and evaluated through the
492 VSM, as well as confirms our initial hypothesis that " *Lean Manufacturing highlights the waste produced in*
493 *a circular industrial system, which allows its subsequent improvement*". This can be seen in greater detail in
494 the different indicators associated with each dimension. In the case of the conventional VSM metrics
495 (economic metrics), the waiting times and inventories related to the remanufacturing and refurbishment
496 processes, can be seen through the time line and lead times, which show different production rates and
497 capacities. In the case of environmental metrics, waste is observed through the consumption of water,
498 energy and resources. In the case of the social metrics, the different indices associated with each workplace
499 are shown and finally, in the case of the circular dimension, it is evidenced through the longevity and
500 circularity of each branch of the system.

501 **6. Discussion and Conclusions**

502 Through the present research it was possible to establish a relationship between the concepts of value and
503 waste under the Circular Economy and Lean Manufacturing philosophy, which allowed to define specific
504 metrics to evaluate the circular systems. According to the information found in the literature, these metrics
505 correspond to the economic, social, environmental, and circular dimensions. Subsequently, the indicators
506 corresponding to each metric were determined through the adaptation of the VSM tool, to which the
507 circularity and longevity indicators were proposed and added to consider the value related to the Circular
508 Economy.

509 With the adaptation of the VSM to circular environments, it was possible to prove that this tool can be
510 useful to represent this type of systems and obtain relevant information to support decision making from
511 an operational perspective. In addition, with the inclusion of these new indicators, a clearer global vision is
512 projected, which includes new dimensions that allow to evaluate a system considering the economic,
513 social, environmental and circular performance.

514 With the application of the mapping in the case study, it was possible to determine that a **circular product**
515 **(generated through a closed loop by refurbishment and/or remanufacturing processes) will not necessarily**
516 **be better than a linear product (generated through the linear process)**, for this it is necessary to consider all
517 the dimensions mentioned above.

518 Finally, it was possible to test the hypothesis, allowing to prove that a system composed of different loop
519 closures can be represented and evaluated through the VSM and it was shown how a Lean approach can
520 support the improvement of a circular system. Waste and improvement opportunities could be detected
521 and corrected with future proposals, in order to increase the value in the system.

522 The limitations of this research are linked to the fact that the information gathered for the case study came
523 from the literature and was complemented with empirical information provided on websites and
524 assumptions of the authors. In addition, it is important to note that there is very little evidence in the
525 literature that can link Circular Economy with Lean philosophy.

526 For future research we recommend the use of the Circular VSM in practical case studies, where more
527 specific field information can be obtained, as well as its application in different production systems for
528 further validation.

529 **7. Acknowledgments**

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532

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