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Interpreting the Smartphone Life Cycle Through Smarta

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ABSTRACT Many complex systems, such as the product life cycle (PLC), can be described in terms of networks, with elements interacting and based on terms of graph theory. In this article, we intend to analyze the PLC from the point of view of network theory and chaos. To do this we will use the Smarta software, developed by our research group (but not yet in a commercial phase), based on network analysis and that allows us to interpret the virtuous circles that the system possesses, and analyze the causalities by observing the plot of existing relationships between the system's attractors. Smarta allows us to manage the uncertainty of whether or not the product is ecological, and to be proactive, in the sense of designing strategies that anticipate it. A case study is the PLC of a smartphone, where Smarta will act as a filter since it will allow us to associate the concepts of ecological and attractor, so that if the product is recyclable an attractor will be found, and if it is not recyclable it will lack attractors.

INDEX TERMS Circular economy, attractors, networks, product life cycle.

I. INTRODUCTION

General Systems Theory (GST) focuses on the study of systems from a global perspective, without taking into account the nature of the elements and relationships that compose them [1]. The major advantage of this theory, developed by Bertalanffy, is that it can be applied to many disciplines: economics, tourism, social systems, biology, etc.

Graph Theory also plays a major role in system modelling, as it helps us identify the network of variables within a system together with their interconnections. One notable example in the case of economic systems is the input-output model established by Leontief [2]. This model has proven to be essential to analyse an economy's interdependencies and to calculate a company's total output based on final demand.

Within economic systems, the Product Life Cycle (PLC) process was put forward by Levitt in the field of marketing [3]. The PLC describes a temporary period from the moment a product enters the market until it leaves the market. Beyond this classical concept of PLC, another more extensive and current interpretation takes into account all the materials or processes that intervene in the product from the moment it is created until it dies or is recycled. This article is based on this latter understanding of the PLC.

Although from Levitt's position, every PLC process would consist of four phases (introduction, growth, maturity and decline), currently other authors propose that more phases be included in this process. Specifically, Chen *et al.* suggest seven stages [4]: (1) product design, (2) process development, (3) product manufacturing, (4) sales, (5) product in use, (6) postsell service and (7) retirement.

Likewise, as regards the types of PLC models, authors Can and Folan propose two categories: M-PLC and E-PLC [5]. The M-PLC (or Marketing PLC) models are designed to meet the requirements of marketing. On the other hand, the E-PLC (Engineering PLC) models incorporate design and manufacturing with marketing requirements.

Although many types of products display this former PLC market behaviour, products classified as ''ecological'' act differently. Indeed, somes authors define a product as ''ecological'' when it fulfills two conditions: (a) its functions are equivalent to those of its corresponding non-ecological

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product and (b) the damage it causes to the environment during its life cycle is substantially inferior to that caused by its non-ecological counterpart [6].

In this sense, companies are trying to introduce the concept of green marketing (or environmental marketing) in the PLC of these products. Peattie defines green marketing in the following way: ''the holistic management process responsible for identifying, anticipating and satisfying the needs of customers and society, in a profitable and sustainable way'' [7], [8]. While it is true that many consumers doubt whether a product offered by a company really meets the conditions of being ecological, Chamorro and Bañegil say that ecolabels are not simply marketing tools, but are true indicators that ensure that a product is green and, in turn, demonstrate the philosophy of a company with respect to ecological marketing [9].

One of the fundamental bases underlying ecological marketing (and on which this article is based), would be the philosophy ''Cradle to Cradle'' (C2C), a concept developed by McDonough and Braungart [10]. This interpretation can be understood as the process of devising, designing and producing imitating the processes of nature, so that the elements that make up the products (technical/biological nutrients) can be 100% reused or recycled.

In addition, the results obtained in this work represent a mathematical interpretation of the PLC, and of the circular economy in general. One of the most interesting definitions of circular economy would be that of Geissdoerfer *et al.*, who understand it as a system capable not only of regenerating itself, but also of optimizing the consumption of resources, and minimizing the generation of waste, emissions and energy leaks, being necessary to close, narrow and slow down the loops of material and energy [11]. Thus, Europe and China would be two clear examples of regions that pursue this type of economy [12]– [14].

As for PLC applications, we find authors such as Haanstra *et al.*, who advance biological and technical cycles and combine them in the butterfly diagram that describes the basis of the circular economy [15]. Other more quantitative interpretations, such as that by Tyagi *et al.*, include a mathematical model that stretches the cost of the PLC [16]; or that of Spragg, who applied the Bass diffusion model (which describes how new products are acquired according to the demands of innovative buyers and imitators) and the Newsvendor model (used to deduce the optimal thresholds to control inventories) to the specific case of the fashion market [17]. Another interesting case is that of Matsuyama *et al.*: these authors present a method to model the PLC by simulating the life cycles of the entities (products, parts, materials, etc.) during their design phase [18]. To do this, they make use of ''entity information'' (specific status of an individual product) and ''nominal information'' (product design characteristics). With the goal of promoting research in PLC modeling, Acimovic *et al.* provide a database of 8935 weekly orders, which include a total of 170 Dell computer products throughout their life cycle, sold in North America from 2013 to 2016 [19]. In fact, Hu *et al.* use this database to forecast the evolution of orders for new products placed by customers. To do this, they use historical PLC data from previous similar products, select which type of PLC curves best fit the data, and finally, use these curves to predict future orders [20].

The PLC field is also directly related to the concept of closed loops, either because recycling stages appear, or because there are feedback loops between various stages of product production. In this sense, the design of closed loop networks has been used by authors such as Akçali *et al.* [21]. Likewise, Accorsi *et al.* manage the life cycle of a product through a linear programming of strategic design of a network of loops of several steps, where raw materials, manufacturing plants, distribution centers, retailers, waste collection nodes, recycling centers and landfills appear [22]. Finally, Lloret *et al.* use the concept of closed loop through the search for attractors, elements that can be found during the design phase of a product, and that can also serve as an indicator of the success of a company's products [23].

II. APPROACH

In the present article, we propose an original theoretical model that is based on the GST enriched with Graph Theory. Thanks to this model, we are able not only to introduce important concepts such as coverage, invariability, orbits and attractors [24], but also to apply them to the PLC case, based on a cyclic process where products are reused within the framework of the circular economy [25]– [27].

One of the great advantages of this model is that it can be applied to many fields, since it is based on GST. Furthermore, it presents the novelty of approaching systemic analysis from a discrete perspective, unlike the linear perspectives adopted until now. Finally, when locating attractors in the system, it is possible to deduce their next immediate trends and thus go on interpreting the data dynamically based on the new data obtained. This is a major difference with respect to classical statistical methods, which provide results for the present moment.

Regarding our model's limitations, the analysis could be truly complicated when applied to a large scale system. To solve this problem, our research group developed a causal analysis simulator enabling the model to automatically process large amounts of data [28]. Smarta will be used in this article for the presented case study [29].

We analysed a PLC case for a markedly relevant product today: the smartphone. To do this, we applied the Smarta software to the proposed model and deduced the trends of this system. Finally, we also performed a complementary analysis of our case study, making use of different network indicators related to the PLC.

III. SYSTEMIC AND GRAPHICAL INTERPRETATION OF THE PLC

From a systemic point of view, we can interpret the PLC as the pair determined by: the object set and the set of relations.

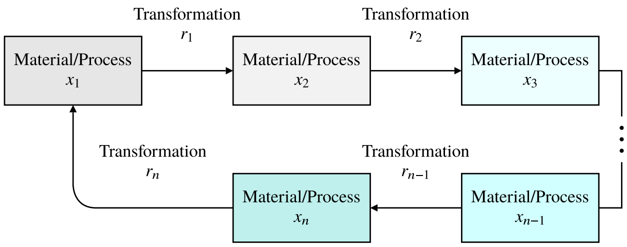


FIGURE 1. **Circular flow in a PLC.**

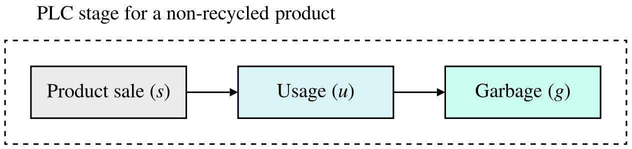


FIGURE 2. **Example of a structural function of a PLC sub-process.**

In our case, the set object will consist of the *materials* and *processes* used in the PLC, while the set of relations is constituted by the *transformations* of the latter materials and PLC processes. If the product is recyclable, a *circular flow* will occur in its PLC (Figure 1). As we can see, the materials/processes would correspond to $x_1, x_2, \ldots, x_n$, while the transformations would match with $r_1, r_2, \ldots, r_n$.

On the other hand, we find the element of *structural function*. In this context, the structural function will correspond to the set of materials/processes in which a specific PLC material/process has been transformed. Usually, the structural function of a material or process x is represented as $f_M(x)$.

To better understand the concept of structural function, let's look at Figure 2, which illustrates a PLC stage corresponding to a non-recyclable generic product. As we can see, this stage would be composed of 3 materials/processes: "Product sale" (s), "Usage" (u) and "Garbage" (g). So, we would say that:

- The structural function of "Product sale" ($f_M(s)$) is "Usage" (u), this is $f_M(s) = u$, because "Product sale" only affects "Usage".
- The structural function of "Usage" ($f_M(u)$) is "Garbage" (g), i.e. $f_M(u) = g$, since "Usage" only affects "Garbage".
- There is no structural function of "Garbage", which would be symbolized as $f_M(g) = \varnothing$, since "Garbage" does not affect any material/process.

Therefore, we could mathematically summarize all of the above in the following way:

$$\begin{aligned} f_M(s) &= \{u\} \\ f_M(u) &= \{g\} \\ f_M(g) &= \varnothing \end{aligned} \tag{1}$$

Coverage is a property relative to the direct influences or transformations of a PLC stage. In this sense, the coverage would indicate to us what is the structural function associated to a concrete stage of the PLC. If A and B are stages (or sets of materials/processes) of the PLC, then we will say that A covers B, if met that $f_M(A) = B$. Similarly, if A covers B, then all materials/processes in set A will only be transformed into materials/processes in set B.

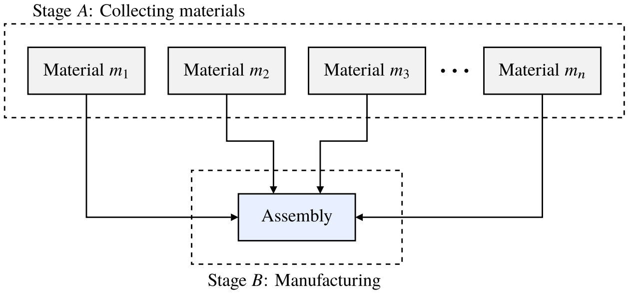


FIGURE 3. **Coverage example. Stage *A*, made up of the materials $m_1, m_2, m_3, \ldots, m_n$, covers stage *B*, made up solely of the assembly process.**

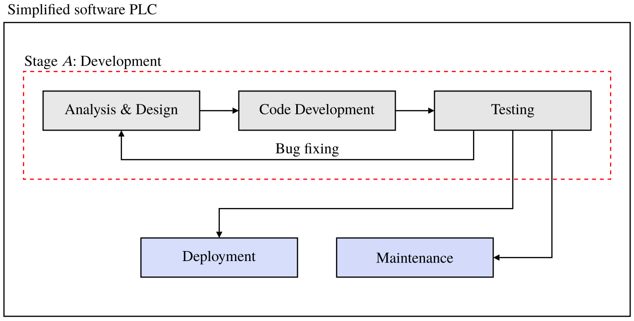


FIGURE 4. **Example of simplified software PLC. Stage *A* would cover the entire "Simplified software PLC" stage.**

Figure 3 illustrates an example of coverage. In this case, we can observe two stages: stage A ("Collecting Materials"), formed by the materials $m_1, m_2, m_3, \ldots, m_n$; and stage B ("Manufacturing"), constituted solely by the "Assembly" process. Note that stage A covers stage B, since all the materials of A only influence the sole process of B. Therefore, we know that it is verified that $f_M(A) = B$, which written in developed form would be:

$$f_M(m_1, m_2, m_3, \ldots, m_n) = \left\{ \bigcup_{i=1}^{n} f_M(m_i) \right\} = \{\text{Assembly}\} \tag{2}$$

On the other hand, Figure 4 shows a software's simplified PLC. Worthy of note, this system includes a smaller stage A system ("Development"), formed by the processes "Analysis & Design", "Code development" and "Testing". Stage A would cover the entire "Simplified software PLC" stage, since it influences all the processes of the latter. Analytically, it would be fulfilled that:

$$f_M \begin{pmatrix} \text{Analysis \& Design,} \\ \text{Code development,} \\ \text{Testing} \end{pmatrix} = \begin{Bmatrix} f_M(\text{Analysis \& Design}) \cup \\ f_M(\text{Code development}) \cup \\ f_M(\text{Testing}) \end{Bmatrix} \tag{3}$$

$$f_M\begin{pmatrix}\text{Analysis \& Design,}\\ \text{Code development,}\\ \text{Testing}\end{pmatrix} = \begin{Bmatrix}\text{Analysis \& Design,}\\ \text{Code development,}\\ \text{Testing,}\\ \text{Deployment,}\\ \text{Maintenance}\end{Bmatrix} \tag{4}$$

Therefore, for this to happen, some circular flow must appear within stage A. We can also observe that, depending on the nature of the product (software in this case), a circular flow does not necessarily imply that the product will be recycled, but if a product is recycled, then it will have some circular flow. For example, in the case of software, the stage A loop constitutes the "Bug fixing" procedure, during which the possible failures of the application under development are corrected.

The idea of *invariant set* may be interpreted as a set which, while keeping its structure and status, remains constant with respect to any type of relation. In the PLC context, an invariant set would correspond with exit stages, that is, sets of materials/processes that generate a frontier effect, since no transformations leave the stage in which they are immersed.

For example, many industrial materials are generally not renewable, such as thermoset plastics. These types of material cannot be recycled because when the temperature increases, these polymers degrade instead of melting. Therefore, the closest approach to recycling these types of plastics is usually by using them as filling material or by chemical dissociation [30].

Figure 5 shows an example of PLC for thermoset plastic. During the polymer manufacturing stage (A), the "Thermosetting resin" material is transformed by chemical curing into "Thermosetting plastic" material. The manufactured polymer is then sold to different industry sectors (Electronics, Aerospace, Energy, etc.), which, in turn, will use it in required applications (stage B). Finally, since this material cannot be recycled, it is used as much as possible as a filling material or for chemical dissociation (stage C). In this example, stages A and B would not be invariant, since relationships or transformations are emitted. However, stage C would be invariant, because no relationships are formed, thus ending the PLC flow.

When the associated structural function iterates indefinitely on any other subset, this gives rise to what we may coin as the term *orbit* of a variable or subset of variables. A material's orbit or x process within the PLC corresponds to the set of materials/processes that we can reach from x. It can be represented as $Orbf_M(x)$.

Figure 6 shows an example of a simplified PLC for a recyclable glass container. As we can see, the process begins with the manufacturing of glass bottles and their subsequent distribution to packaging companies, which fill them with the products they sell. Next, the packaged products are sold to different stores, where customers will buy them to consume them. When the product has been consumed, the customer takes the glass bottles to a recycling point where they will be collected and transported by truck to the processing plant. At this latter plant, glass waste is transformed into cullet, a raw material used to manufacture new bottles.

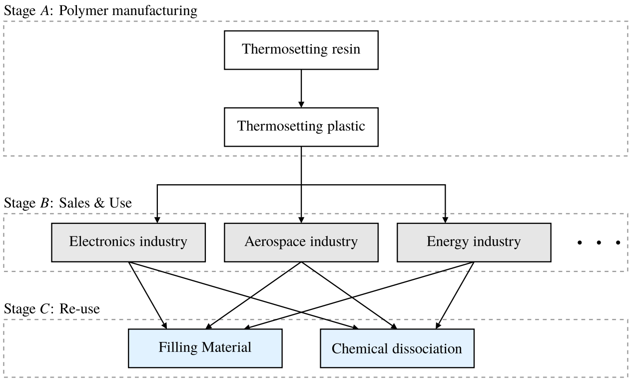


FIGURE 5. Example of simplified PLC for thermosetting plastic. Stages *A* and *B* would not be invariant, while *C* would be invariant.

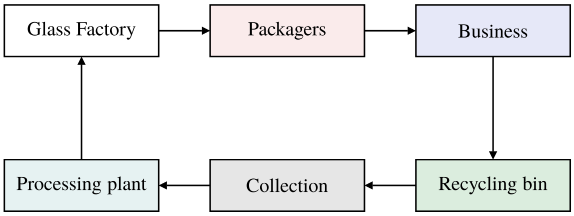


FIGURE 6. Simplified PLC of a recyclable glass packaging.

In the example above, the "Glass Factory" process orbit would consist of all chain processes that we can reach from "Glass Factory", which corresponds in this case to the complete PLC:

$$Orbf_M(\text{Glass Factory}) = \begin{Bmatrix}\text{Packagers, Business,}\\ \text{Recycling bin, Collection,}\\ \text{Processing plant,}\\ \text{Glass Factory}\end{Bmatrix} \tag{5}$$

Worthy of note, since this PLC is a circular flow, all the processes' orbits will be identical and will coincide with the complete PLC. Extending this idea, the orbit of a stage A of the PLC will be the set of all the chains of materials/processes associated with the elements of A.

Finally, we find one of the most important elements: the *attractors*. Attractors are zones of attraction that delimit the behaviour of apparently disorganised variables; these areas of attraction make it possible to predict certain related behaviour.

The attractors will be in charge of showing us towards which set of materials/ processes the PLC tends over time. In this sense, the attractors will indicate both the most relevant circular and invariant flows of the PLC, as well as the different chains of materials/processes associated with these loops.

Attractors are crucial within a PLC, because thanks to them we can find out analytically whether a product can become recyclable or not. We will come back to this question more in depth in section V.

IV. PLC-RELATED NETWORK INDICATORS

As we have seen, the PLC of a product can be modeled by a set of materials/processes related to each other through transformations. Therefore, it is inevitable to compare the representation of this model with a directed graph (or digraph), where the materials/processes would correspond with the nodes of the graph, and the transformations with its edges. Specifically, one of the disciplines grouped together by Graph Theory is of interest: Network Theory. In this sense, a *network* would consist of a system formed by *actors* (nodes) that are connected through *ties* (edges). The concept of network broadens the concept of conventional graph, since both the actors and the ties can have *attributes*, that is to say, characteristics that allow them to differentiate between themselves [31]. For example, in the case of the PLC, materials/processes could have as an attribute to which stage of the process they belong (manufacturing, development, recycling, etc.), while transformations could have as an attribute the type of relationship between materials/processes (type of agreement between companies, type of customer to whom the product is directed, degree of complexity of the product recycling process, etc.).

The fact of using in a complementary way the Network Theory in the field of the PLC, allows to open a great range of possibilities, because we can make use of different indicators that help us to characterize numerically the network associated to the PLC under study. The most interesting network indicators that can be applied in the case of the PLC could be: network density, average degree, degree centralization (input and output), diameter and average distance. Let us now analyse these parameters adapted to the PLC network.

Network density (ND) is a percentage that reflects the degree of connections or transformations between PLC materials/processes. It is the quotient between the number of current transformations of the PLC network (T) and the number of maximum transformations it could have ($T_{\max}$), that is:

$$ND = \frac{T}{T_{\max}} \cdot 100 = \frac{T}{N \cdot (N-1)} \cdot 100 \tag{6}$$

Since the PLC network is directed (relations have direction) and a material/process does not influence itself (it does not autotransform), the number of maximum transformations that could exist would be $T_{\max} = N \cdot (N-1)$, where N would be the number of materials/processes in the network. The reason for this value is that, in the maximum case where each material/process was connected to all others, there would be $N-1$ connections for that material/process. As we would have a total of N materials/processes, there would be a total of $N \cdot (N-1)$ maximum connections in the PLC.

Therefore, a value of ND close to 0% would indicate a poorly connected PLC, while a value close to 100% would refer to a very connected PLC.

Another parameter that indicates the level of connections would be the *average degree* (AD), which is defined as the current number of PLC transformations (T) divided by the total number of materials/processes (N):

$$AD = \frac{T}{N} \tag{7}$$

Thus, this indicator would inform us about the number of average transformations per material/process within the PLC. The values of AD could vary from 0 (no material/process connected) to $N-1$ (each material/process connected to all others).

The *degree centralization* (C_D) allows us to find out how central is the most central material/process of the PLC network. The expression that allows us to calculate this indicator would be the following:

$$C_D = \frac{\sum_{i=1}^{N} (C_D(n_{\max}) - C_D(n_i))}{\sum_{i=1}^{N} \left(C_D(n^*_{\max}) - C_D(n^*_i)\right)} \tag{8}$$

For that:

1) We obtain the centralities of each one of the materials/processes of the PLC ($C_D(n_i)$), adding all the transformations associated with the material/process n_i.
2) We calculate the differences $C_D(n_{\max}) - C_D(n_i)$ for each of the PLC materials/processes, where $C_D(n_{\max})$ would correspond to the material/process with the highest centrality value.
3) We add all the above differences to obtain the numerator of the expression.
4) We repeat steps 1), 2) and 3) for the case of a PLC network of the same size as our PLC (N), which has the shape of a perfect star ($N-1$ peripheral materials/processes joined only to a central material/process). Thus, we obtain the denominator of the expression.

As equation 8 compares the sum of differences in centrality of our PLC with the sum of differences for the case of maximum centrality, C_D could vary between 0 and 1. Thus, a PLC that constitutes a circular flow would have a low centralization value (close to 0), while a PLC that does not contain flows would have a higher centralization value (close to 1).

The degree centralization C_D is often used in non-directed (symmetric) networks. However, since a PLC network is directed (asymmetric), it is more common to express centralization through two parameters: *in-degree centralization* ($C_{D,in}$) and *out-degree centralization* ($C_{D,out}$). These centralizations not only make it possible to quantify how central the most central material/process of the PLC is, but also provide information on the direction of the transformations associated with that material/process. Equations 9 and 10 would allow us to calculate these two indicators.

$$C_{D,in} = \frac{\sum_{i=1}^{N} \left(C_{D,in}(n_{\max}) - C_{D,in}(n_i)\right)}{(N-1)^2} \quad (9)$$

$$C_{D,out} = \frac{\sum_{i=1}^{N} \left(C_{D,out}(n_{\max}) - C_{D,out}(n_i)\right)}{(N-1)^2} \quad (10)$$

As we can see, these centralizations would be calculated in the same way as the degree centralization, but with 2 differences: (1) the centrality of each material/process, $C_{D,in}(n_i)$, would be calculated by adding all transformations entering that material/process, while $C_{D,out}(n_i)$ would be calculated by adding all transformations leaving that material/process; (2) for both $C_{D,in}$ and $C_{D,out}$, the denominator of their expressions would be $N-1$, a value that would correspond to the sum of centrality differences in the case of a perfect star-shaped PLC, where the central node receives all the transformations from the peripheral nodes (case of $C_{D,in}$), or where the central node emits all the transformations to the peripheral nodes (case of $C_{D,out}$). As in degree centrality, indicators $C_{D,in}$ and $C_{D,out}$ could take values between 0 and 1.

The *diameter* (D) can be defined as the shortest distance between the 2 most remote materials/processes within the PLC network. Analytically, we would have that:

$$\begin{aligned} &D = \max\left\{d(n_i, n_j)\right\}, \quad \forall n_i \text{ connected to } n_j \\ &i = 1, 2, \ldots, N \\ &j = 1, 2, \ldots, N, \ (j \neq i) \end{aligned} \quad (11)$$

To do this, we calculate the minimum distance $d(n_i, n_j)$ between each pair of materials/processes connected from the PLC, that is, the minimum number of transformations that allows us to reach from the material/process n_i to the material/process n_j. Finally, we get the maximum value of all previously calculated minimum distances. Note that the distances of a material/process with itself ($d(n_i, n_i)$) are not taken into account, since this scenario will not be found in a PLC network. This indicator would inform us of the linear size of the PLC network.

The *average distance* ($\bar{d}$) consists of the average of all the minimum distances between the materials/processes connected from the PLC, i.e.:

$$\begin{aligned} &\bar{d} = \frac{\sum d(n_i, n_j)}{M}, \quad \forall n_i \text{ connected to } n_j \\ &i = 1, 2, \ldots, N \\ &j = 1, 2, \ldots, N \ (j \neq i) \end{aligned} \quad (12)$$

where M would correspond to the total number of pairs connected inside the PLC. In this sense, the lower the value of $\bar{d}$, the lower the amount of average transformations to go from a material/process n_i to another n_j, while if the value of $\bar{d}$ is large, there will be many average transformations to get from n_i to n_j.

The parameters analysed above are usually calculated using network analysis software, such as Ucinet or Gephi [32], [33]. In the present article, we will use these indicators in a complementary way to characterize numerically the PLCs under study.

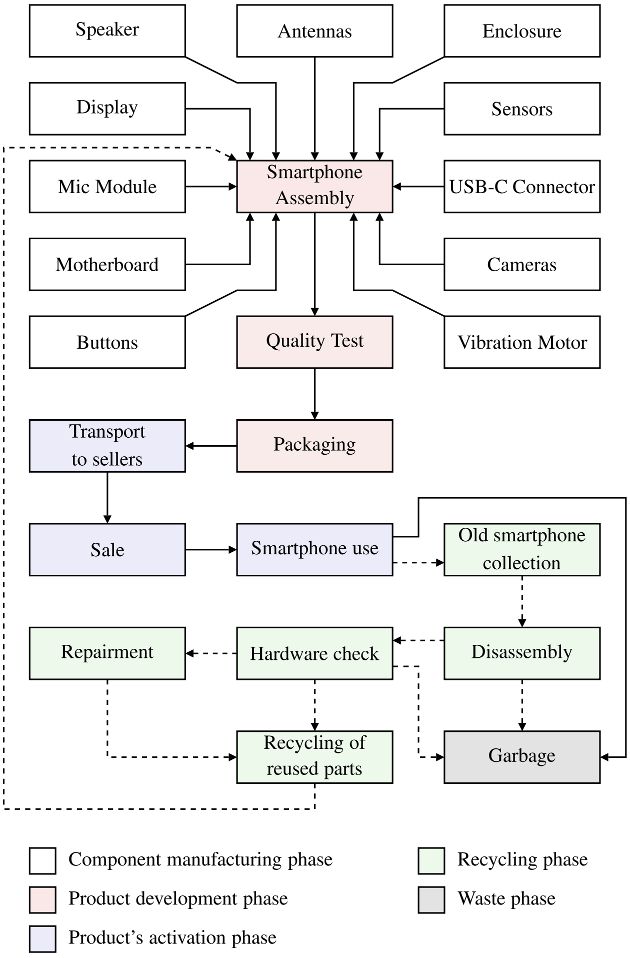
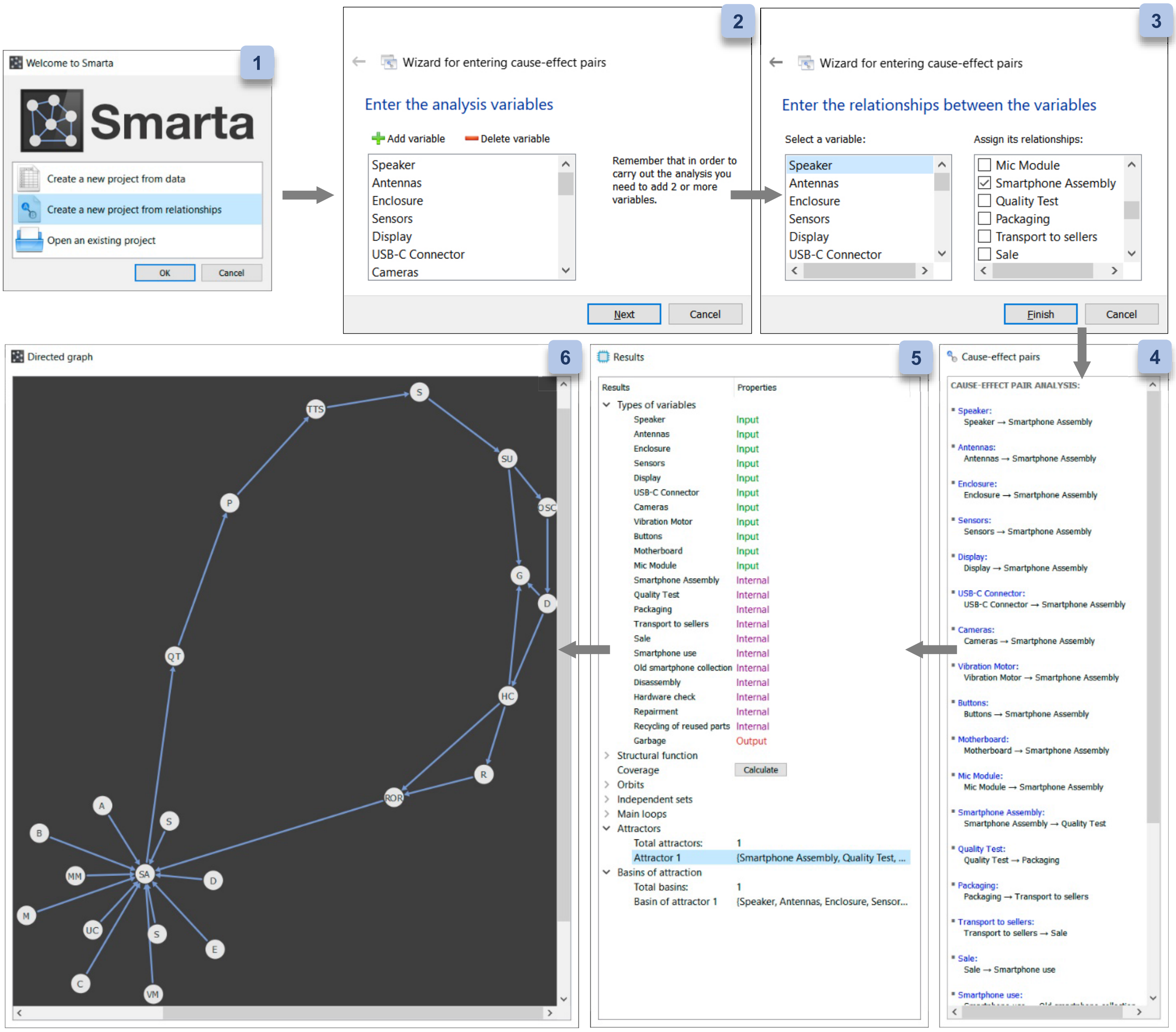


FIGURE 7. **PLC of a smartphone.**

V. CASE STUDY

To apply the proposed modelling technique, we will select a current case study: the PLC of a smartphone (Figure 7).

As we can see, the PLC starts with the manufacturing of all the components and electronic modules necessary for mounting the smartphone (motherboard, display, cameras, etc.). This phase of manufacturing and configuration of raw materials is represented in the diagram; the processes are shown in white. Next, all the mentioned components are assembled in the assembly plant, where the devices will be later programmed. Then, quality tests are performed and the packaging is prepared so that the smartphones are ready for distribution. This stage constitutes the product development phase and is represented by the processes in red. The next phase would be the product's activation phase: it includes transport to companies selling consumer electronics, the sale of the smartphone and the use of the terminal by the end user. This stage is illustrated by the processes in blue. Once the smartphone is obsolete, the user disposes of the product,



Enter the analysis variables

Speaker
Antennas
Enclosure
Sensors
Display
USB-C Connector
Cameras

Remember that in order to carry out the analysis you need to add 2 or more variables.

Enter the relationships between the variables

Select a variable:
Speaker
Antennas
Enclosure
Sensors
Display
USB-C Connector

Assign its relationships:
☐ Mic Module
☑ Smartphone Assembly
☐ Quality Test
☐ Packaging
☐ Transport to sellers
☐ Sale

CAUSE-EFFECT PAIR ANALYSIS:

- Speaker:
  Speaker → Smartphone Assembly
- Antennas:
  Antennas → Smartphone Assembly
- Enclosure:
  Enclosure → Smartphone Assembly
- Sensors:
  Sensors → Smartphone Assembly
- Display:
  Display → Smartphone Assembly
- USB-C Connector:
  USB-C Connector → Smartphone Assembly
- Cameras:
  Cameras → Smartphone Assembly
- Vibration Motor:
  Vibration Motor → Smartphone Assembly
- Buttons:
  Buttons → Smartphone Assembly
- Motherboard:
  Motherboard → Smartphone Assembly
- Mic Module:
  Mic Module → Smartphone Assembly
- Smartphone Assembly:
  Smartphone Assembly → Quality Test
- Quality Test:
  Quality Test → Packaging
- Packaging:
  Packaging → Transport to sellers
- Transport to sellers:
  Transport to sellers → Sale
- Sale:
  Sale → Smartphone use
- Smartphone use:

Results	Properties
Types of variables	
Speaker	Input
Antennas	Input
Enclosure	Input
Sensors	Input
Display	Input
USB-C Connector	Input
Cameras	Input
Vibration Motor	Input
Buttons	Input
Motherboard	Input
Mic Module	Input
Smartphone Assembly	Internal
Quality Test	Internal
Packaging	Internal
Transport to sellers	Internal
Sale	Internal
Smartphone use	Internal
Old smartphone collection	Internal
Disassembly	Internal
Hardware check	Internal
Repairment	Internal
Recycling of reused parts	Internal
Garbage	Output
Structural function	
Coverage	Calculate
Orbits	
Independent sets	
Main loops	
Attractors	
Total attractors:	1
Attractor 1	{Smartphone Assembly, Quality Test, ...
Basins of attraction	
Total basins:	1
Basin of attractor 1	{Speaker, Antennas, Enclosure, Sensor...

FIGURE 8. PLC analysis of a smartphone via the Smarta application.

either by taking it directly to the garbage (waste stage, the "Garbage" process is shown in grey), or transporting it to an available recycling point (following the recycling stage, the processes are shown in green). These points are usually located in the stores themselves during their mobile renewal campaigns. The technicians disassemble the old terminals and verify the quality of the components, checking if they can be reusable. At this stage, different options present themselves: (1) if the component was badly damaged and repairing it is inviable, it ends up at the waste stage; (2) if the component is in perfect condition it can be recycled, thus closing a circular flow and contributing to the creation of new devices; and (3) if it is viable to repair the component, the repair would be performed and the device subsequently recycled.

As we can see, this PLC would be a 5-stage system, with a total of 23 materials/processes. To examine this case, we turned to Smarta, a causal analysis software implemented by our research group for this purpose. First of all, after executing Smarta, we created a new project based on relationships, since the relationships or transformations between variables (materials or processes) are already known beforehand (Figure 8, step 1). Next, we add and name all the PLC variables in the Smarta cause-effect pair assistant (Figure 8, step 2) and, for each variable, we introduce all its relationships (Figure 8, step 3). After finishing this process, we will be able to see in the corresponding panel all the cause-effect pairs introduced, that is to say, all the influences of each one of the variables of the PLC of the smartphone (Figure 8, step 4). Then, we obtain all the results of the analysis, in terms of types of variables, structural functions, coverage, orbits, independent sets, main loops, attractors and attraction basins (Figure 8, step 5). Finally, the application allows us to represent an interactive directed graph associated with the system under study, in order to facilitate its interpretation (Figure 8, step 6).

For this case study, Smarta provided us with a single attractor (A) linked to the smartphone PLC:

$$A = \left\{ \begin{array}{c} \text{Smartphone Assembly, Quality Test, Packaging,} \\ \text{Transport to sellers, Sale, Smartphone use,} \\ \text{Old smartphone collection, Disassembly,} \\ \text{Hardware check, Repairment,} \\ \text{Recycling of reused parts, Garbage} \end{array} \right\} \tag{13}$$

The localised attractor would coincide with the system's main loop and the material/process assemblies that we can reach from this loop.

For this example, the attractor would be formed by all stages except the first (manufacturing of the components, represented in white). This phenomenon occurs because the recycling stage (in green) allows a circular and invariant flow to be completed within the smartphone's PLC, so the system's attractor set is automatically generated. As we can see, if we follow the chain of transformations of any material or PLC process we will always end up in the A attractor set. Therefore, if a product is recyclable and thus forms a circular flow, it will all be reflected in the attractor.

Furthermore, Smarta can also display the *attraction basin* (C) associated with attractor (A), which in this case would coincide with the complete set of materials and processes of the PLC, that is to say:

$$C = \left\{ \begin{array}{c} \text{Speaker, Antennas, Enclosure, Sensors,} \\ \text{USB - C Connector, Cameras, Vibration Motor,} \\ \text{Buttons, Motherboard, Mic Module, Display,} \\ \text{Smartphone Assembly, Quality Test, Packaging,} \\ \text{Transport to sellers, Sale, Smartphone use,} \\ \text{Old smartphone collection, Disassembly,} \\ \text{Hardware check, Repairment,} \\ \text{Recycling of reused parts, Garbage} \end{array} \right\} \tag{14}$$

The attraction basin is important because following the chain of successive transformations of any material or process in the basin leads us to the system's attractor. On the other hand, if the recycling stage was not present in the PLC, the diagram shown in Figure 7 would be obtained, but eliminating all the materials/processes coloured in green, as well as the transformations represented with a dashed stroke. When entering the data in Smarta and launching the processing, we would notice that the software does not return any associated attractor to the PLC, since the invariant circular flow of the system has been cut off. Similarly, since there is no attractor (A), there will be no associated attraction basin (C) either, so:

$$C = A = \varnothing \tag{15}$$

These two PLC examples illustrate the relevance of an attractor within the PLC: if the product is recyclable then it will have an attractor, and will coincide with the system's invariant main loops and with the stages in which the processes of these circular flows are transformed. In contrast, a non-recyclable product will lack an attractor, because there will be no invariant circular flows within the PLC.

To finish this part, we will carry out an analysis of the smartphone PLC through the indicators detailed in section IV. As can be seen, Table 1 shows the values of the parameters studied, both for the PLC network with and without recycling stage.

TABLE 1. Network indicators for smartphone PLC case with and without recycling stage.

Indicator	*Symbol*	*With recycling*	*No recycling*
Size	N	23	18
Transformations	T	26	17
Network density	ND	5.1%	5.6%
Average degree	AD	1.130	0.944
In-degree centralization	$C_{D,in}$	0.517	0.626
Out-degree centralization	$C_{D,out}$	0.089	0.003
Diameter	D	10	7
Average distance	$\bar{d}$	5.502	3.714

In the first place, we can point out that the size of the network with recycling is larger than without recycling, because it contains a total of 23 materials/processes and 26 transformations, unlike the network without recycling, which would have 18 materials/processes and 17 transformations.

However, in the case of the network without recycling, the network density is slightly higher (5.6% versus 5.1%). This is due to the fact that for the recycling stage, although new materials/processes have been introduced ("Old smartphone collection", "Disassembly", "Hardware check", "Repairment" and "Recycling of reused parts"), there are not many transformations associated with these that increase the *ND* ratio enough to surpass the case of non-recycling. We can also appreciate that for both PLCs we find a very low value of *ND* (less than 6%). The reason would be that both networks have a linear structure (the output of one material/process is the input of the next), so that each material/process does not have a large number of connections.

On the other hand, we can distinguish that the average degree for the network with recycling (1.130 transformations per material/process) is higher than that of the network without recycling (0.944 transformations per material/process). This small increase is due to the fact that by adding the recycling stage, there are several materials/processes that increase the average number of network transformations, such as "Smartphone use", "Disassembly", "Hardware check", "Recycling of reused parts" and "Garbage".

In terms of in-degree centralization, the network without recycling would be slightly higher than the network with recycling (0.626 vs. 0.517). The justification for this phenomenon lies in the fact that for the case without recycling, the structure of the network would be somewhat more centralized (it would look more like a perfect star), thus observing that there are several transformations that are directed towards the most central materials/processes (''Smartphone Assembly''). On the other hand, by introducing the recycling stage in the network, its structure is decentralized, since now there are other central nodes besides ''Smartphone Assembly'', such as ''Recycling of reused parts'' and ''Garbage''. This favors the linearization of the network structure, thus moving it away from the star configuration. Note that for both cases, the centralization values have an intermediate magnitude (0.626 and 0.517 over a maximum of 1), which would indicate that the PLCs related to the smartphone industry pursue circularity and distance themselves from centralization.

For the out-degree centralization, we can appreciate that the values in both cases are practically negligible (0.089 with recycling and 0.003 without recycling). These low values respond to the fact that in both networks the most central node (''Smartphone Assembly'') has a receiver behavior, as it receives a total of 12 and 11 transformations for the case of recycling and non-recycling, respectively. Also, in the PLC with recycling there is a higher value of output centralization, mainly because there are several central nodes, such as ''Smartphone use'', ''Disassembly'' and ''Hardware check'', which have a more emitting behavior than the rest of materials/processes in the network.

As far as the diameter of both networks is concerned, in the case of the PLC with recycling we would obtain a value of 10, that is, we must go through a minimum of 10 transformations to reach from any material/process of the component manufacturing stage (''Display'', ''Speaker'', ''Antenna'', etc.) to the furthest node (''Repairment'' and ''Recycling of reused parts''). This would make sense, as introducing a recycling stage would increase the complexity of the PLC. On the contrary, for the PLC without recycling we would have a value of 7, so we have to go through 7 transformations to be able to go from the beginning (''Display'', ''Speaker'', ''Antenna'', etc.) to the end (''Garbage'').

Finally, the PLC with recycling would indicate a greater average distance (5.502) than in the case of the PLC without recycling (3.714). This would mean that, in the case of recycling, the materials/processes would be separated by a greater number of average transformations than in the case of the PLC without recycling. Therefore, we see that in order to introduce the recycling phase in the life cycle of the product, it is necessary to sacrifice proximity between materials/processes, which would imply a greater time, cost and complexity of processing in the PLC of the smartphone.

VI. CONCLUSIONS

The European Union is betting on the circular economy and the stakes are high: the circular economy generates employment and decisions regarding the manipulation of product life cycles through reusing, repairing and recycling are of crucial importance.

We carried out a systemic modelling of the PLC, based on the GST, networks theory and a specific version of discrete chaos theory, which has never been applied to this context until now. We also applied the proposed model to concrete examples of PLCs of different kinds of products.

Furthermore, we checked the relevance of the concepts of ''circular flow'' and ''invariability'' within the PLC both when modelling the system's loops and when detecting the stages that produce a frontier effect within the PLC. Both concepts gave rise to the notion of attractor, that is to say, sets towards which the PLC tends over time, and the existence of which allows to deduce whether a product will be recyclable or not.

In addition, we have studied several interesting network indicators that can be applied to the case of PLC, which can help us quantify numerically this type of networks.

To validate our proposal, we implemented and described the case study of a smartphone's PLC. In this way, we were able to verify that when a recycling stage exists within a PLC, an attractor is produced that indicates that the product in question is recyclable. However, by eliminating the recycling phase, the invariant circular flow of the PLC is stopped, so the attractor is eliminated, meaning that the product will not be recyclable.

Finally, thanks to the analysis of network indicators, we have been able to discover that the PLC's of smartphone companies that pursue the philosophy of the circular economy have more cyclical structures, and therefore, with a greater degree of complexity and decentralized structures.

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