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An approach to Evaluate the Impact of the Introduction of a Disassembly Line in Traditional Manufacturing Systems

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Abstract:

Purpose: The circular economy (CE) paradigm, traditionally based on the 3R (reuse, recycle, and remanufacture) principles, provides benefits for sustainability and represents a big opportunity for manufacturing enterprises to reduce costs and take economic advantages. This paper proposes an approach that can help stakeholders transition towards CE oriented business by evaluating the economic convenience of introducing a manual disassembly line to recover the components of End-of-Life (EoL) products in a traditional manufacturing system.

Design/methodology/approach: The conceptual approach is generic and based on the characteristics of EoL products and on the reusability and recyclability features of every component. Then, based on the type of product and the disassembly sequence, the disassembly line is built in the virtual environment along the assembly line. The virtual environment must take into account the probabilistic parameters that characterise each real industrial context. Therefore, the assembly-disassembly lines are linked with the variables and economic functions needed to process the outputs of the approach application.

Findings: Implemented in a virtual environment, the proposed approach evaluates a priori possible economic and environmental benefits coming from the integration of a disassembly line within a manufacturing context. The approach considers the variability of the EoL products' status (their reusability and recyclability indices), provides the optimal number of operators that must be assigned to the manual disassembly line and determines the maximum reduction of the product cost that can be gained by introducing the disassembly line. Furthermore, an application example is provided to show the potential of the tool.

Originality/value: Recently, the scientific literature has dealt with the issue related to the disassembly process of EoL products from several perspectives (e.g. disassembly line scheduling, planning, balancing, with and without the consideration of the quality of EoL products). However, to the best of our knowledge, no study provided an approach to evaluate the convenience of the investment in a disassembly line. Therefore, this document contributes to this research field by proposing a simple approach that supports the decision-making process of traditional manufacturing enterprises to evaluate a priori the economic return (i.e. how much the product cost decreases) and provide an estimate of the environmental benefits of integrating a manual disassembly line of EoL products with a traditional manufacturing system.

Keywords: circular economy, end-of-life products, sustainable manufacturing, economic performance

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1. Introduction

Nowadays, manufacturing industries are addressing several challenges aimed at reaching new economic, environmental and social goals to achieve sustainable production processes (Eslami, Dassisti, Lezoche & Panetto, 2019; Franciosi, Voisin, Miranda, Riemma & Iung, 2020). To this end, several studies have explored the trends and research challenges in sustainable manufacturing and examined how rethinking business processes contributes to the sustainable performance of manufacturing firms (Franciosi, Di Pasquale, Iannone & Miranda, 2020; Garetti & Taisch, 2012). These studies are a necessary step in contributing to the circular economy (CE) paradigm.

CE principles aim to increase resource use efficiency to achieve a better balance and harmony between the economy, environment and society (Ghisellini, Cialani & Ulgiati, 2016). Traditionally CE is based on the so-called 3R principles, i.e. reuse, remanufacture and recycle, which respectively aim to reuse the product directly at the end of its life cycle; remanufacture a used product to restore it to its original performance, specifications and warranty; and recycle the product to reuse its materials and reduce resource consumption and pollution generation (Acerbi & Taisch, 2020). These three principles are eased practically by disassembly processes that allow the disassembling of sub-components for the reuse, remanufacture and recycle of materials. Disassembly is facilitated by a proper product design, which is fundamental for the application of CE principles (Favi, Marconi, Germani & Mandolini, 2019). Consequently, this pushes producers to re-think the product design to ease product disassembly at the end of a product's life, facilitating its recovery. Therefore, the conventional 3R has become the 6R principles, adding the three principles of 'recovery', 'redesign' and 'remanufacturing' (Jawahir & Bradley, 2016).

Research on the CE paradigm has evolved primarily on waste generation, environmental impact, and resource use, while business and economic perspectives are often neglected (Lieder & Rashid, 2016). However, the application and consideration of CE principles leads to both a limitation of natural resource consumption and environmental concerns and to economic and individual business advantages (Ormazabal, Prieto-Sandoval, Jaca & Santos, 2016). The CE business model is opening new possibilities for organisations (Pietro-Sandoval, Torres-Guevara, Ormazabal & Jaca, 2021) in terms of cost and environmental impact optimisation that will be crucial for the survival of organisations in the near future. For these reasons, the management of End-of-Life (EoL) products becomes an essential process that, if conducted correctly, saves resources, reduces the amount of wastes, otherwise destined for ecological islands or incineration and leads also to economic advantages (Sergio, Franciosi & Iannone, 2021).

Therefore, besides the environmental advantages, CE model allows the creation of highly skilled jobs and economic growth, saves on the disposal costs that manufacturers must support by law (Benthaha, Voisin & Marangé, 2020) and promotes economic savings, by recovering the residual value contained within products after the end of their first useful life (Marconi & Germani, 2017).

The recovery of EoL products can be carried out directly by manufacturing companies, which through a proper strategy and the integration of disassembly lines in their processes can benefit from economic (reduction of purchase costs for new components and virgin materials), environmental (e.g. the reduction of CO_2 emissions) and social (e.g. in terms of company image, new employee hires) advantages. Therefore, the provision of approaches and tools aimed at assessing the economic and environmental convenience of the introduction of disassembly lines in manufacturing enterprises, should be crucial for evaluating a-priori the best disassembly line configuration to reduce manufacturing impacts on sustainability.

To this end, this study provides insights by developing an approach that can help stakeholders transition towards a new CE-oriented business to evaluate the possible economic and environmental benefits that a manual disassembly line for recovering EoL products could have on the product cost of a traditional manufacturing system.

The remainder of this paper is structured as follows: Section 2 presents an overview of the pertinent literature on the disassembly process for CE, Section 3 provides the proposed conceptual approach and the implementation of the approach in the virtual environment, and Section 4 presents an application of the approach and the conducted experiments aimed to show the approach's potentiality. Section 5 provides the conclusions of the work and possible further steps in this research.

2. Literature Overview

The disassembly process can be described as the systematic separation of constituent parts from EoL products through a series of operations. To properly recover EoL products, the disassembly process is the key link connecting product returns with product recovery, a prerequisite for other processes, and the main gateway of information (Priyono, Ijomah & Bititci, 2016). Therefore, the disassembly process should be seen from a strategic perspective in manufacturing firms to meet CE principles.

Very recently, the existing literature has examined the disassembly process in industrial manufacturing realities that meet CE principles from many perspectives that are reported in the following.

First, to promote the disassemblability of products, the product needs to be designed to ease the disassembly process. Several existing studies discuss Design for Disassembly (DfD) (Abuzied, Senbel, Awad & Abbas, 2020; Soh, Ong & Nee, 2014; 2015), which goes beyond the scope of this paper but is an important research area affecting the disassembly process. The product design can strongly influence disassembly times and processes (Mandolini, Favi, Germani & Marconi, 2018).

Several recent papers have focused on the specific problem of disassembly line balancing and have proposed approaches and methods to optimise this issue, considering several aspects that can influence it as well as different types of EoL products. In 2016, Igarashi, Yamada, Gupta, Inoue and Itsubo (2016) presented a practical model and design of multi criteria optimisation that allowed for lower disassembly costs, higher recycling and higher CO_2 saving rates by an environmental and economic parts selection, and subsequent disassembly line balancing. In the same year, Xia, Li, Tian, Zhou, Li, Tian et al. (2016) developed a suitable disassembly sequence for the Chinese end-of-life vehicles (ELV) disassembly industry, while Seidi and Saghari (2016) proposed a fuzzy disassembly line balancing problem with multiple objectives that allocate disassembly tasks to the ordered group of disassembly work stations. Their proposed method has been utilised to balance automotive engine disassembly line in fuzzy environments. Zheng, He, Chu and Liu (2018) provided a model for the disassembly line balancing problem based on stochastic task processing times, aiming to minimise the costs of the disassembly workstation and the processing of hazardous components. Taking into account that disassembly processes are labour intensive, some authors have addressed the disassembly line balancing problem while considering aspects connected with human and environmental safety (Kazancoglu & Ozkan-Ozen, 2020). Assuming that more than one operator is allocated to a disassembly station to overcome the problem of a larger space requirement and longer disassembly time (occurring in the case of one resource allocated to each station), other authors aimed to optimise the number of workers and workstations (Cevikcan, Aslan & Yeni, 2020). Recently, Budak (2020) proposed a disassembly line balancing approach that was integrated into a sustainable reverse logistics network problem.

Other papers have focused on the planning of the disassembly sequence, which plays a crucial role in the reuse and remanufacturing of EoL products (Li, Zhang, Yan, Jiang, Wang & Wei, 2019). However, achieving optimal disassembly sequences is a complex problem. Therefore, some recent studies proposed solutions to this issue, such as a method for disassembly planning of waste electrical and electronic equipment (Nowakowski, 2018); two methods for defining an optimal disassembly sequence, which were tested on a case study (Francia, Ponti, Frizziero & Liverani, 2019); an approach to determine an optimised disassembly sequence and disassembly stopping point that maximises economic benefits and minimises environmental costs (Smith, Hsu & Smith, 2016); and an algorithm to the disassembly sequence decision making (Zhao, Li, Fu & Yuan, 2014). Liu, Zhou, Pham, Xu, Ji and

Liu (2020) considered the aspects related to disassembly line balancing and planning and proposed an algorithm to solve the collaborative optimisation of robotic disassembly sequence planning and the robotic disassembly line balancing problem.

Determining the sequence of disassembly operations is called disassembly planning and is a one-time decision, but another decision must be taken, i.e. determining the quantity of components that will be disassembled with timing decisions, which is referred to as disassembly scheduling (Gökgür, Gökçe & Özpeynirci, 2015). A disassembly sequence plan is one of the inputs of the disassembly scheduling plan, which, unlike disassembly planning, has to be made for each planning horizon, based on demand, availability, capacity, and other constraints. Other recent papers focus on this last specific issue: Nonoyima and Tanimizu (2017) proposed a disassembly scheduling method which adopted a genetic algorithm to generate an optimal disassembly schedule including both the disassembly processes of multiple products and the post processes for reusing and recycling the disassembled parts for the minimization of the whole disassembly and post process times; Ehm (2019) presented a data-driven modelling approach to the problem related to the integrated disassembly process planning and machine scheduling; whereas Gökgür et al. (2015) focused on the capacitated disassembly scheduling problem with the aim of maximising profit.

Other recent articles have focused on other specific aspects influencing the disassembly processes, i.e. the quality of EoL products. Rickli and Camelio (2014) proposed an approach that addressed the impact of EoL product quality uncertainty on partial disassembly sequences, whereas Colledani and Battaia (2016) presented a decision support system to support operators in adjusting the disassembly sequence based on the measured key quality characteristics of the EoL products. Recently, Bentaha, Voisin and Marangé (2020) provided a decision tool for the disassembly process planning, taking into consideration the quality of the products to be disassembled and aiming to maximise the profit of the disassembly process.

A few articles also considered integrating the remanufacturing process. For example, Fu, Zhou, Guo and Qi (2021) investigated a disassembly-reprocessing-reassembly scheduling problem to achieve the expected makespan and total tardiness minimisation, whereas Guiras, Turki, Rezg and Dolgui (2018) investigated optimising the disassembly, remanufacturing and assembly system by using a robotic arm manipulator for the assembly and disassembly processes. Finally, Tahirov, Hasanov and Jaber (2016) proposed a mathematical model to optimise a closed-loop supply chain of multi-items with returned subassemblies and identified which strategy (remanufacturing, production or mixed) was more viable.

The papers reported so far addressed topics related to the disassembly process of EoL products, focusing on different specific aspects of this research field, but without providing an approach that helps to evaluate the convenience of the investment in a disassembly line. Therefore, taking the reusability and recyclability features of EoL products into account, this article provides a simple approach that supports the decision-making process of traditional manufacturing enterprises to evaluate a priori the economic convenience (i.e. how much the product cost decreases) and an estimate of the environmental benefits of integrating a manual disassembly line of EoL products with a traditional manufacturing system. In other words, this approach can help entrepreneurs to evaluate if invest and how much is the economic convenience in the investment for introducing a disassembly line, showing them with which arrival rate of the EoL products the investment is convenient, evaluating the trade-off among costs and revenue. The approach proposed in this study considers the effects of the input probabilistic parameters (i.e. the EoL product status and the reusability and recyclability indices of EoL components) on the economic feasibility and provides the optimal number of operators necessary for the manual disassembly line as well as an estimate of the CO_2-eq emissions that such a system could save.

This paper is a natural consequence of the previous study conducted in Sergio et al. (2021), that focused on the conceptual model on which the approach proposed in the current paper is based. Therefore, after an exhaustive recap of the main contents of the previous document, this paper proposes the implementation of the approach in a virtual environment, providing the details related to the tool design and parametrisation.

Then, Section 3 reports the details of the approach proposed in this study, and Section 4 provides an example of an application.

3. The Proposed Approach

The proposed approach analyses the economic impact of the introduction of a disassembly line to support an assembly line in manufacturing systems. The proposed approach is not specific to a kind of product but can be adapted through in-depth studies of the item and the market to define the technical and economic parameters that have been identified.

The entire manufacturing system is outlined in the Assembly/Disassembly Department, as shown in Figure 1, which presents the IDEF0 scheme with all the detailed information needed for the design of the logical model. Such information includes the inputs (new components, EoL products), resources (workstations, operations, buffers) and control parameters (number of workstations, number of operators, Bill of Materials (BOM), Queue priority, Quality standards, Work shifts) that are needed to generate the main outputs (finished products, materials for recycling, scrap materials).

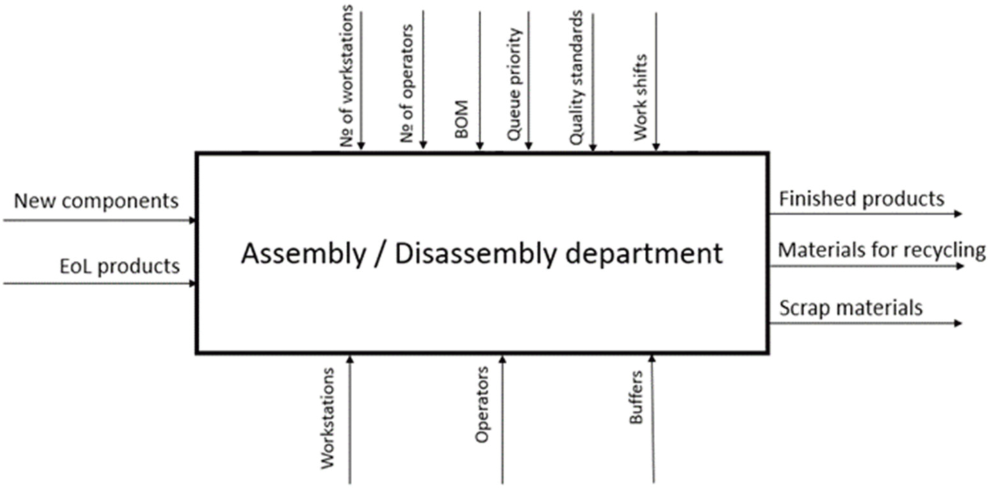


Figure 1. Model IDEF0 scheme (Sergio et al., 2021)

Figure 2 provides a low-level representation of the logical of the model (Sergio et al., 2021). The EoL products enter the disassembly line, which is composed of several disassembly stations, and the disassembly operators manually decompose the product, according to a rigid sequence. Each phase of the sequence is responsible for the recovery of a component, which is then directed to the reuse process (assembly line in Figure 2, comprising several assembly stations), the recycling process or the disposal, according to the values of specific reusability and recyclability indices that provide information about the state of the components.

Using the reusability index (Equation (1)), it is possible to evaluate the probability that a disassembled component can be reinserted into the assembly processes to realise new products, while the recyclability index (Equation (2)) assesses the percentage of mass of recovered material that can be recovered from recycling processes. The reusability index directly affects every single disassembly operation, weighing on the final number of components that can actually be reused, while the recyclability index plays a role in calculating the amount of new raw material that can be obtained from the recovered parts and directed through the recycling process (Figure 3).

The reusability index for the i-th component is calculated as follows:

$$I_{r,i} = D_i * M_{D,i} \tag{1}$$

where D_i represents the disassembly index and reflects the possibility that the disassembly operation may cause even a partial breakage of the component, and $M_{D,i}$ is the degradation index of the material, which is the use function exercised by the end user during the component's useful life.

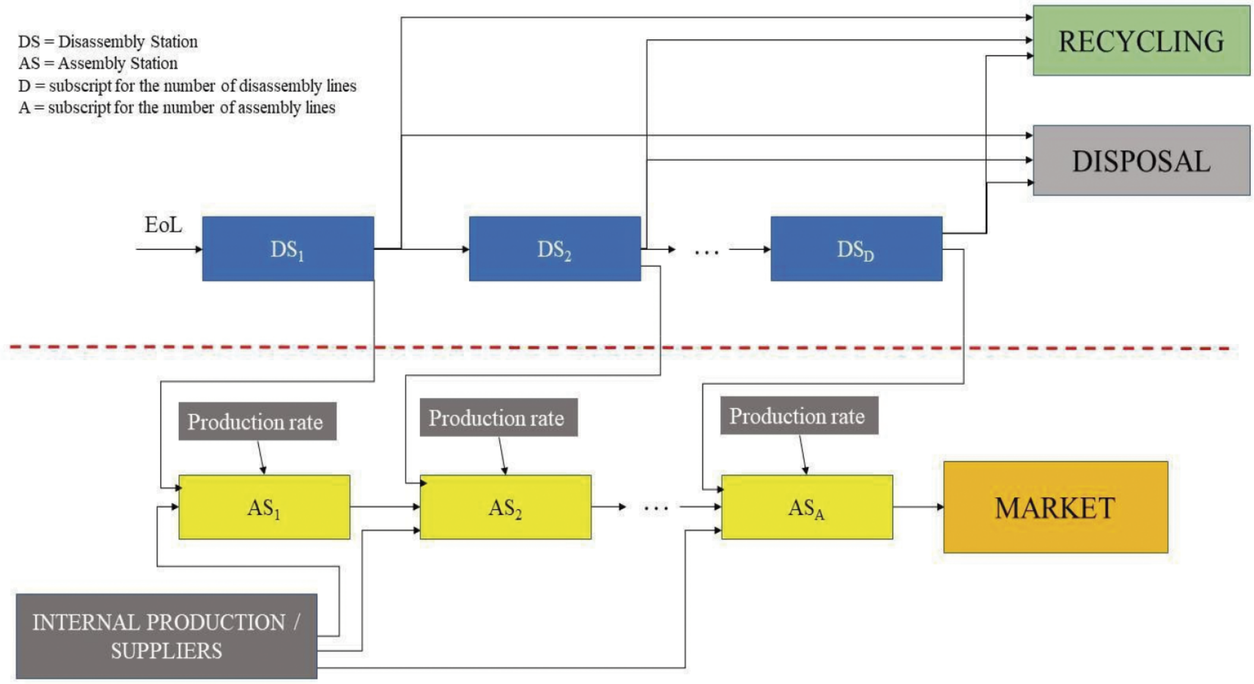


Figure 2. Assembly/disassembly lines (Sergio et al., 2021)

The recyclability index for the i-th component is calculated as follow:

$$I_{rec,i,m} = D_i * M_{r,m} * C_{i,m} \tag{2}$$

For the m-th material of the i-th component, the recyclability of the material ($M_{r,m}$) is dependent on the technological recycling processes and the contamination index ($C_{i,m}$), which takes into account, for example, the possibility that the material is contaminated by particular substances.

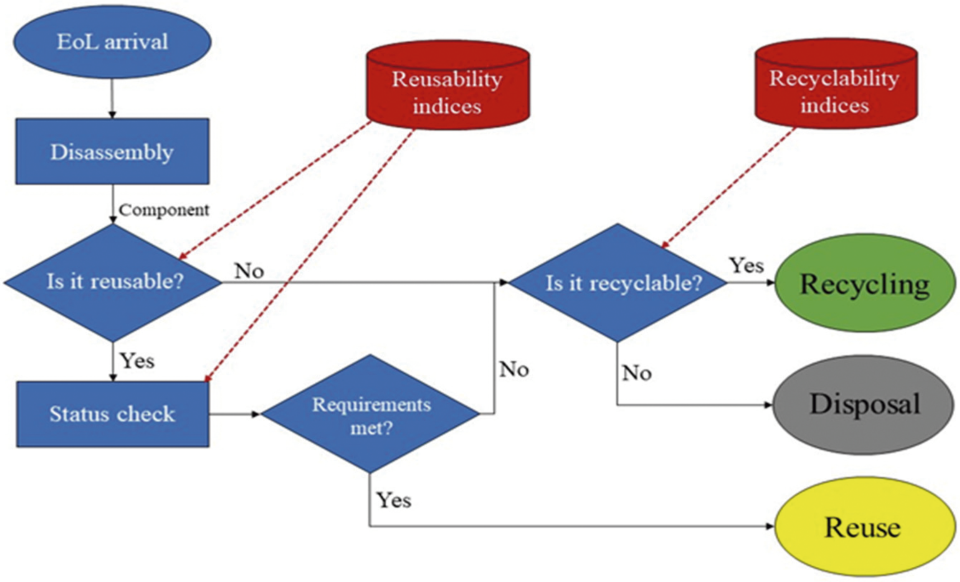


Figure 3. Disassembly and verification process at the workstation (Sergio et al., 2021)

The approach evaluates the unit cost of a new product coming out of the assembly line, considering the introduction of a disassembly line (Equation (3)). The Equation (3) consists of three addends at the numerator: the unit cost of manpower for assembly and disassembly lines, where N_{ass} and N_{dis} represent respectively the number of operators involved in assembly and disassembly lines, $c_{m,h}$ is the hourly cost of labour and t is the time considered for the analysis; the unit cost of components C_{comp} (new or recovered from EoL); and the possible revenue from recycled materials (reported in the equation as a reduction of cost, R_{rec}). At the denominator, the variable $N_{FP}(T)$ provides the number of final products [pcs] requested by the market and processed by the assembly line in the simulated period T.

$$C_u(T) = \frac{(N_{ass} + N_{dis}) * c_{m,h} * t + C_{comp}(T) - R_{rec}(T)}{N_{FP}(T)} \tag{3}$$

Equation (3) can be used to estimate the effect that introducing a manual disassembly line has on the unit cost of the product and to evaluate the optimal number of operators for the disassembly line that enable the production cost to be minimised.

Finally, since the new processes lead to a lowering of the production demand for new components and trigger the production of new raw material from recycled sources, the model estimates the reduction of the environmental impact, using the index, reported in the Equation (4), δ_{GWP} [$kg_{CO2\text{-}eq}/kg$]:

$$\delta_{GWP,j} = Y_{GWP,j} - Y'_{GWP,j} \tag{4}$$

where GWP refers to the global warming potential, Y_{GWP} [$kg_{CO2\text{-}eq}/kg$] and Y'_{GWP} [$kg_{CO2\text{-}eq}/kg$] represent respectively the quantity of $CO_2\text{-}eq$ emitted to produce 1 kg of material j from virgin sources and from waste materials.

Therefore, the CO_2 savings emitted are given by Equation (5), which considers the contributions made by reuse and recycling:

$$Saving_{CO2-eq} = Q_{EoL} * \left(\sum_{i=1}^{N} \sum_{j=1}^{M} (\alpha_i * m_{i,j} * I_{r,i} * Y_{GWP,j}) + \sum_{i=1}^{N} \sum_{j=1}^{M} (\alpha_i * m_{i,j} * I_{rec,i,j} * (1 - I_{r,i}) * \delta_{GWP,j}) \right) \tag{5}$$

where Q_{EoL} is the quantity of EoL products entering the system, N and M are, respectively, the sets of components and materials of the Bill of Materials, α_i is the coefficient of employment of the i-th component, and $m_{i,j}$ [kg] is the mass of the j-th material in the i-th component.

To evaluate the convenience domain inside a probabilistic context, a virtual environment allowed us to transfer the approach into a software tool that can store and manage many parameters and provides an application interface for potential stakeholders who handle input and output values.

The approach was implemented using AnyLogic 8.7.2 for University, a virtual environment that allowed us to recreate industrial scenarios in a realistic way, using the software's calculation and optimisation process to provide a tool to the end-user to estimate the economic convenience of introducing disassembly processes in an existing manufacturing plant, and to determine the suitable number of disassembly operators. In particular, the optimisation process used by Anylogic consists of repetitive simulations of a model with different parameters. Using sophisticated algorithms, AnyLogic varies controllable parameters from simulation to simulation to find the optimal parameters for solving a problem.

The implementation of the software involved the following phases:

1. Design of disassembly and assembly lines through the appropriate concatenation of logic blocks (Section 3.1);
2. Tool parametrisation through the introduction and setting of input and output parameters and the formulas necessary for the calculations (Section 3.2);
3. Setting the case study and launching the tool (Section 4).

3.1. Tool Design

Following the schematisation of the logical model reported in Section 3, the tool was designed in the software system. The lines that consider all the resources (operators, workstations, power lines, etc.), how they are physically connected to each other and how they transform the inputs into system outputs were schematised and realised in the Anylogic virtual environment.

The disassembly department is logically represented in the software environment as constituted by a conveyor system that transports the EoL and connects the intermediate stations where the EoL product is broken down. Each station represents a decomposition phase from which the reusable, recyclable and disposable components are obtained. The relative probability is represented by the chosen probability distributions, which are functions of the reusability index and the age of the EoL product. The EoL products enter the system through a single block located upstream of the entire process. For each new EoL that enters the system, the internal 'age' parameter is initialised with a random value extracted based on the probability distribution chosen and strictly linked to the product and market characteristics. Then, the EoL products pass to the disassembly line and are moved by a belt conveyor to the various stations, served by a single pool of operators able to carry out all the operations and who therefore, depending on the demand, move from one station to another to disassemble the product. The stations are made up of different types of blocks, depending on whether a component obtained from the operation is potentially reusable. Furthermore, each station is connected to counters that allow quantification of, at each instant, the number of components recovered for each specific destination. In both cases, an operator must be available to complete the disassembly phase: a system with increasing priorities along the process directs the operators to prevent the creation of downstream bottlenecks.

The assembly line is represented at a lower level of detail, as its optimisation is not the aim of this study. It is served by a different pool of operators. Unlike the disassembly line, the assembly line is fed with both new (released on a regular basis) and recovered components (released whenever a recovery occurs in the disassembly line).

When the component enters the assembly line, an internal parameter is initialised with the specific cost associated with the component that depends on the component origin. If the component coming from the disassembly line needs operations to enable its reuse (e.g. cleaning, painting), a unit cost of treatment is considered; however, if the component is new, the associated unit cost of purchase/production is taken into account. Therefore, the components enter a priority queue, which allows the components retrieved from the disassembly line to be assembled.

At the end of each run, the product cost is recorded within a specific variable, i.e. the unit cost of product (see Equation (3)). Furthermore, the software tool records the percentage variation between the product costs with and without disassembly. The system performs various experiments by changing the number of operators in order to find, in a given discrete domain, the value that minimise the product cost with different EoL arrival rates, by exploiting the AnyLogic optimisation process.

3.2. Tool Parametrisation

The different logic blocks are adaptable through internal parameters that allow the operation of the virtual system to be varied. The parameters were grouped into six suitable internal databases containing the values that feed the virtual system:

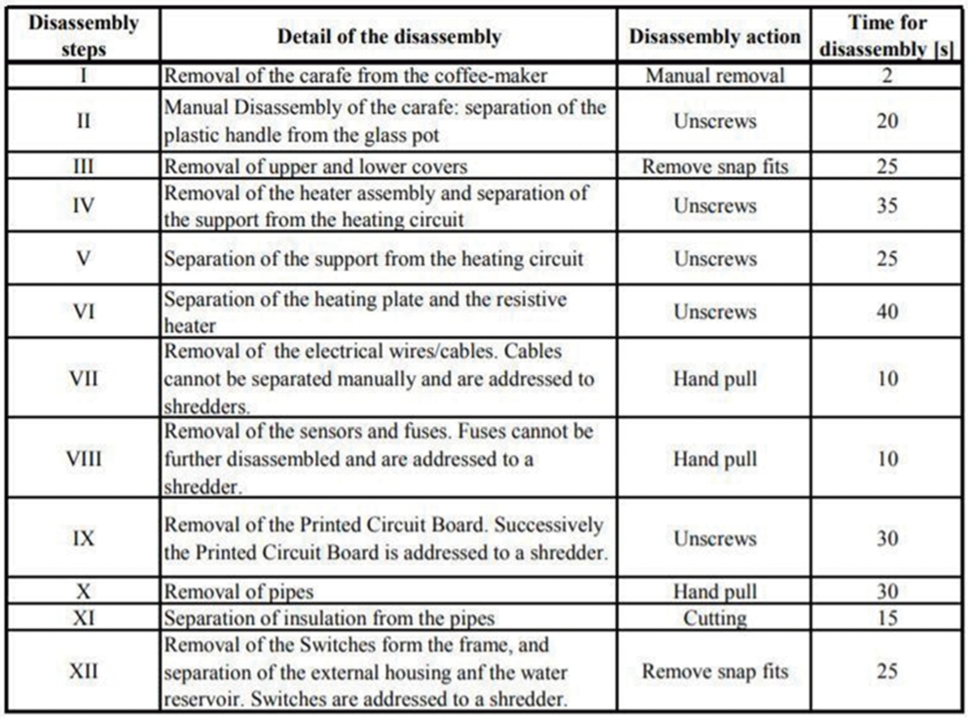
1. *Times*: This database contains the times of the individual disassembly operations in the form of probability distribution; these times regulate the functioning of workstations.
2. *Reuse data*: This database stores data relating to recovery for a new assembly. Specifically, for each of the components, the following data are recorded:
    a) Coefficient of employment (α);
    b) Reusability index (I_r) [%];
    c) Unit cost of treatment [€/pc];
    d) Unit cost of purchase/production [€/pc].

3. *Recycling data*: This database contains data relating to recovery for recycling. Specifically, for each of the materials, the following items were recorded:
    a) Recyclability index (I_{rec}) [%];
    b) Cost of recycling per kg [€/kg];
    c) Selling price per kg [€/kg];
    d) Amount of CO_2 emitted to produce one kg of material from primary sources Y_{GWP} [$kg_{CO2\text{-}eq}/kg$];
    e) Amount of CO_2 saved by producing one kg of material from recovery sources δ_{GWP} [$kg_{CO2\text{-}eq}/kg$];
4. *Component compositions:* This database defines, for each of the components, the quantity in kg present for each material in the bill of materials.
5. *Additional inputs*. The last database contains the following:
    a) Number of disassembly operators;
    b) Hourly labour cost (c_m) [€/h];
    c) Demand for the finished product required by the market (N_{FP});
    d) Arrival rate of EoL products [pcs/h].

4. Coffee Maker Application

This section presents a use case of the tool to show the functioning of the system and the achievable output. The starting product is a typical coffee maker for domestic use.

The disassembly sequence reported in Figure 4 is assumed, through which the layout of the department is modelled (Figure 5 shows, for each station, which components are separated); furthermore, for each phase, the relative calculation of the reference time (i.e. the time of the single disassembly phases) was carried out.



Disassembly steps	Detail of the disassembly	Disassembly action	Time for disassembly [s]
I	Removal of the carafe from the coffee-maker	Manual removal	2
II	Manual Disassembly of the carafe: separation of the plastic handle from the glass pot	Unscrews	20
III	Removal of upper and lower covers	Remove snap fits	25
IV	Removal of the heater assembly and separation of the support from the heating circuit	Unscrews	35
V	Separation of the support from the heating circuit	Unscrews	25
VI	Separation of the heating plate and the resistive heater	Unscrews	40
VII	Removal of the electrical wires/cables. Cables cannot be separated manually and are addressed to shredders.	Hand pull	10
VIII	Removal of the sensors and fuses. Fuses cannot be further disassembled and are addressed to a shredder.	Hand pull	10
IX	Removal of the Printed Circuit Board. Successively the Printed Circuit Board is addressed to a shredder.	Unscrews	30
X	Removal of pipes	Hand pull	30
XI	Separation of insulation from the pipes	Cutting	15
XII	Removal of the Switches form the frame, and separation of the external housing anf the water reservoir. Switches are addressed to a shredder.	Remove snap fits	25

Figure 4. Coffee maker disassembly lines (Ardente, Wolf, Mathieux & Pennington, 2011)

Then, for every step, the relative reference time was used as mode for a triangular probability distribution that simulates the variability of the operation.

Therefore, the reusability and recyclability indices for each component of the coffee maker were calculated (see Figure 6) to obtain information for completing the bill of materials that would populate the tool's internal databases.

The reusability indices are used as a reference for constructing the age-related functions of the individual EoL products that feed the virtual system. These functions require a specific study to determine how much the age of the product contributes to raising or lowering the probability that the various components can be reassembled into new products.

For economic analysis, the definition of the unit cost of several components is needed. By hypothesis, it has been assumed that all new components come from outsourced processes, for which the possible purchase costs have been estimated using a specialised online platform (Custompart, sd), which allows estimates to be made by providing the characteristics of the component as input (Table 1). Instead, the selling price of recycled materials is given by the average values in Table 2. To calculate the savings in CO_2 emissions, the tabulated reference values for the main materials were used (Ardente et al., 2011).

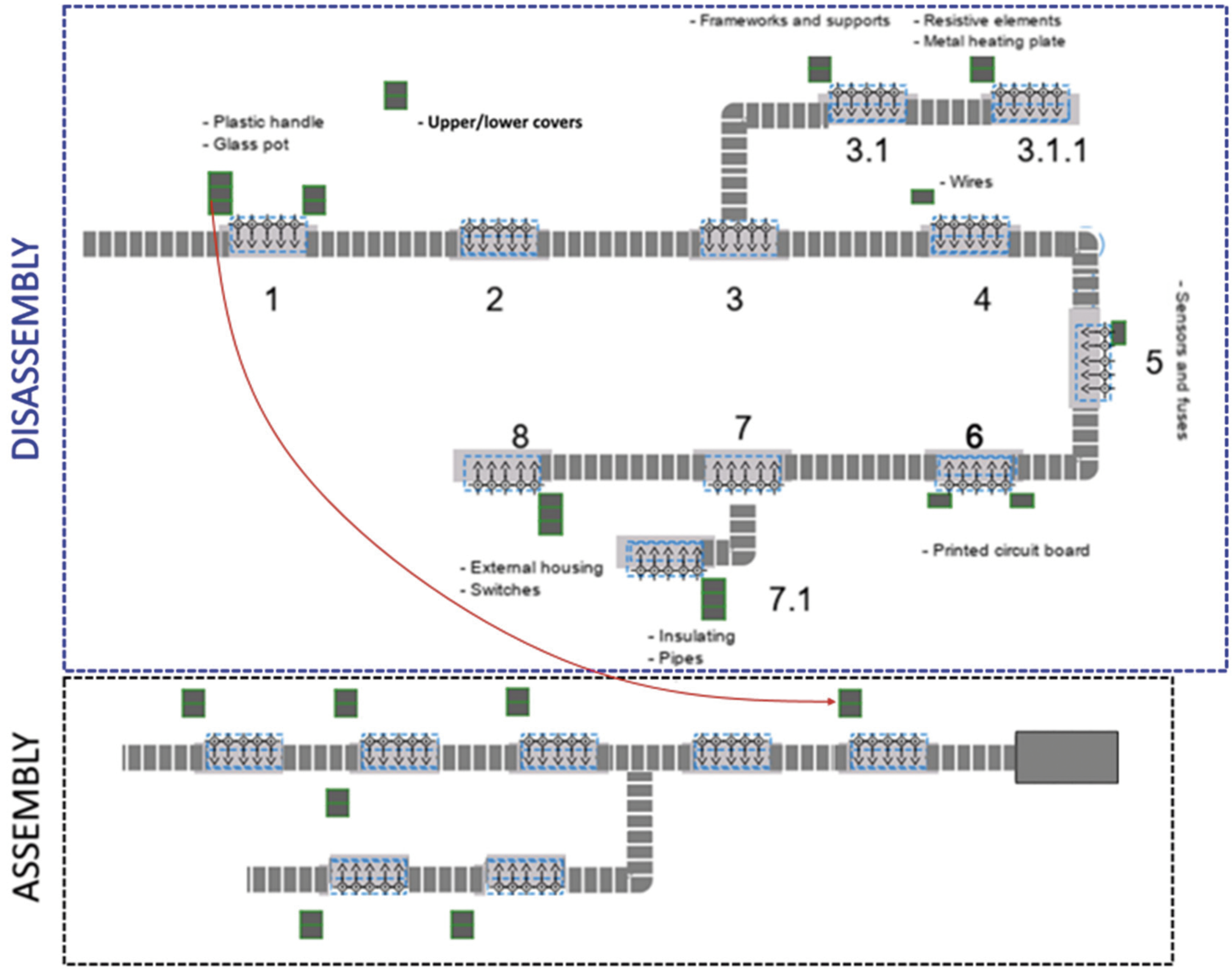
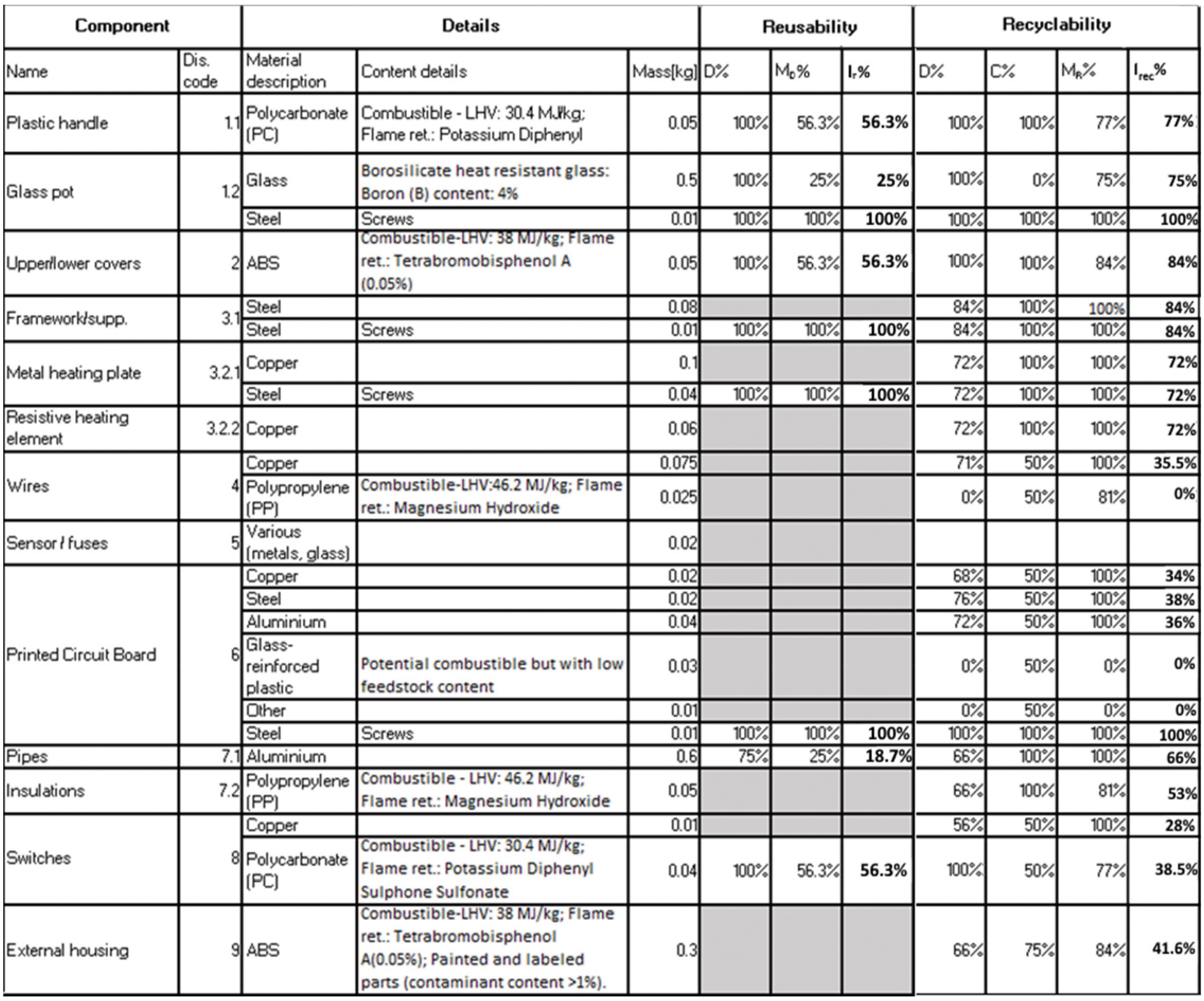


Figure 5. 2D view of the disassembly and assembly lines of the coffee maker in the virtual environment. The red arrow indicates the path of the components recovered by the first disassembly station that will be reassembled as new products



Component		Details			Reusability			Recyclability			
Name	Dis. code	Material description	Content details	Mass[kg]	D%	M_D%	I_r%	D%	C%	M_R%	I_{rec}%
Plastic handle	1.1	Polycarbonate (PC)	Combustible - LHV: 30.4 MJ/kg; Flame ret.: Potassium Diphenyl	0.05	100%	56.3%	**56.3%**	100%	100%	77%	**77%**
Glass pot	1.2	Glass	Borosilicate heat resistant glass: Boron (B) content: 4%	0.5	100%	25%	**25%**	100%	0%	75%	**75%**
		Steel	Screws	0.01	100%	100%	**100%**	100%	100%	100%	**100%**
Upper/lower covers	2	ABS	Combustible-LHV: 38 MJ/kg; Flame ret.: Tetrabromobisphenol A (0.05%)	0.05	100%	56.3%	**56.3%**	100%	100%	84%	**84%**
Framework/supp.	3.1	Steel		0.08				84%	100%	100%	**84%**
		Steel	Screws	0.01	100%	100%	**100%**	84%	100%	100%	**84%**
Metal heating plate	3.2.1	Copper		0.1				72%	100%	100%	**72%**
		Steel	Screws	0.04	100%	100%	**100%**	72%	100%	100%	**72%**
Resistive heating element	3.2.2	Copper		0.06				72%	100%	100%	**72%**
Wires	4	Copper		0.075				71%	50%	100%	**35.5%**
		Polypropylene (PP)	Combustible-LHV:46.2 MJ/kg; Flame ret.: Magnesium Hydroxide	0.025				0%	50%	81%	**0%**
Sensor / fuses	5	Various (metals, glass)		0.02							
Printed Circuit Board	6	Copper		0.02				68%	50%	100%	**34%**
		Steel		0.02				76%	50%	100%	**38%**
		Aluminium		0.04				72%	50%	100%	**36%**
		Glass-reinforced plastic	Potential combustible but with low feedstock content	0.03				0%	50%	0%	**0%**
		Other		0.01				0%	50%	0%	**0%**
		Steel	Screws	0.01	100%	100%	**100%**	100%	100%	100%	**100%**
Pipes	7.1	Aluminium		0.6	75%	25%	**18.7%**	66%	100%	100%	**66%**
Insulations	7.2	Polypropylene (PP)	Combustible - LHV: 46.2 MJ/kg; Flame ret.: Magnesium Hydroxide	0.05				66%	100%	81%	**53%**
Switches	8	Copper		0.01				56%	50%	100%	**28%**
		Polycarbonate (PC)	Combustible - LHV: 30.4 MJ/kg; Flame ret.: Potassium Diphenyl Sulphone Sulfonate	0.04	100%	56.3%	**56.3%**	100%	50%	77%	**38.5%**
External housing	9	ABS	Combustible-LHV: 38 MJ/kg; Flame ret.: Tetrabromobisphenol A(0.05%); Painted and labeled parts (contaminant content >1%).	0.3				66%	75%	84%	**41.6%**

Figure 6. Bill of materials of the coffee maker with reusability and recyclability indices (Ardente et al., 2011)

Component	Cost (€/pc)
Plastic handle	1.5
Glass pot	3
Upper/lower covers	2
Framework supports	0.5
Resistive heating plate	0.5
Metal heating element	0.5
Wires	1.2
Sensor/fuses	1.2
Printed circuit board	5
Pipes	0.7
Insulations	0.07
Switches	0.04
External housing	6.5
Screw	0.005

Table 1. Unit cost of the components of the coffee maker

Material	Average Vm(*) (€/kg)
Aluminium	1.59
Copper	1.77
Steel	0.29
PET	1.68
Paper	0.9
Glass	0.38
PP	0.59
PC	0.89
ABS	0.63

Table 2. Cost of materials. (*) Vm = average price of first production materials
(Villalba, Segarra, Fernandez, Chimenos & Espiell, 2002)

Deterministic arrival rates were used. Every scenario was tested in a discrete range between 0 and 90 pcs/h.

Stations were linked through a conveyor belt characterized by a constant speed of 0.5 m/s and a capacity sufficiently high, compared to the arrival rates, that can be considered infinite.

The simulation time chosen was 880 hours, with repetitions per iteration varying from 5 to 10 (necessary to reach a confidence level of 80%, with a standard error of 0.05); the target variable is the number of operators assigned to the disassembly line.

Several experiments were carried out to verify how the necessary workforce and the cost of the product varied, as the number of EoL products entering the system and the demand for the finished product to be satisfied varied.

Figure 7 presents the results provided by the tool, where shows a slight decrease in the cost of the product for a finished product demand equal to 30 pcs/h, which reaches its maximum with a number of operators equal to 3. Figure 7 also shows that increasing the EoL products inputted does not allow a further reduction in the cost of the product because the capacity of the operators is already saturated; at the same time, increasing the number of EoL products inputted into the system involves a worsening, because the cost of labour exceeds the estimated economic return.

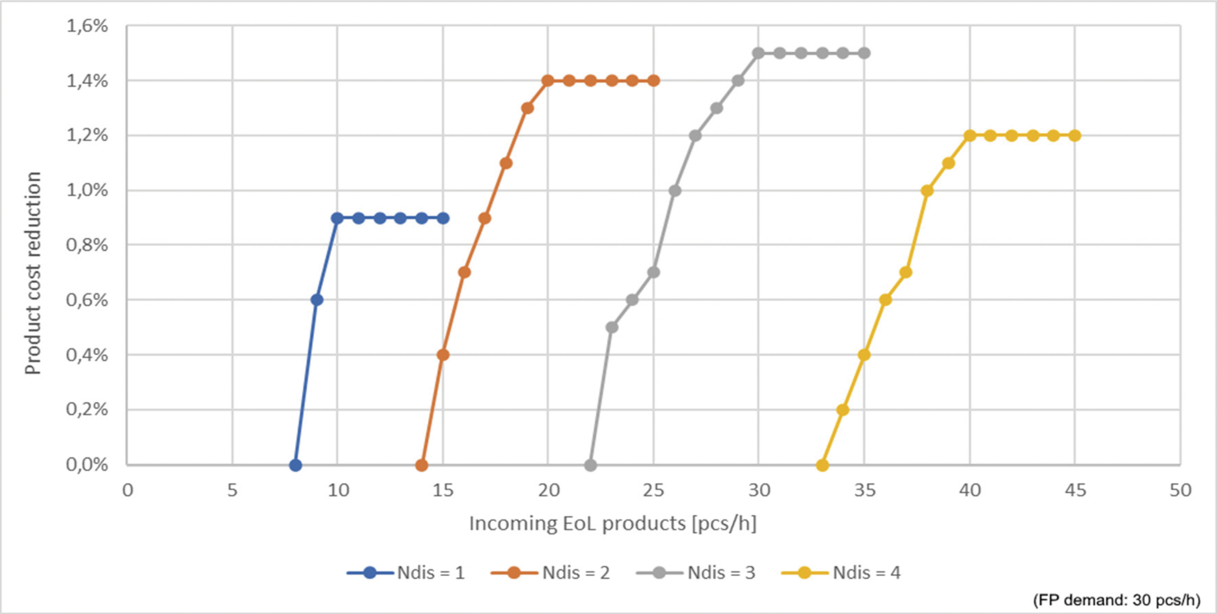


Figure 7. Percentage decrease in the cost of the product as the number of incoming EoL products changes

Figure 8 shows variability of results obtained in correspondence of the peak of every curve in Figure 7, using box plots that testify moderate variability for each iteration, whose mean values were used to build the curves.

Although CO_2 saving in emissions, unlike product cost reduction, is not a target variable of the tool, it is provided as an additional output in order to give evidence of the importance of disassembly for the sustainability of the manufacturing industry: in fact, as shown in Figure 9: simultaneously with the saturation of the operators, there is also a 25% reduction in the environmental impact, that is also an encouraging result in perspective of a potential carbon tax.

It is relevant to note that the product chosen for the example is not designed according to a CE perspective; in particular, the estimated cost reduction is minimal because the components with a higher unit value cannot be reinserted into the assembly process.

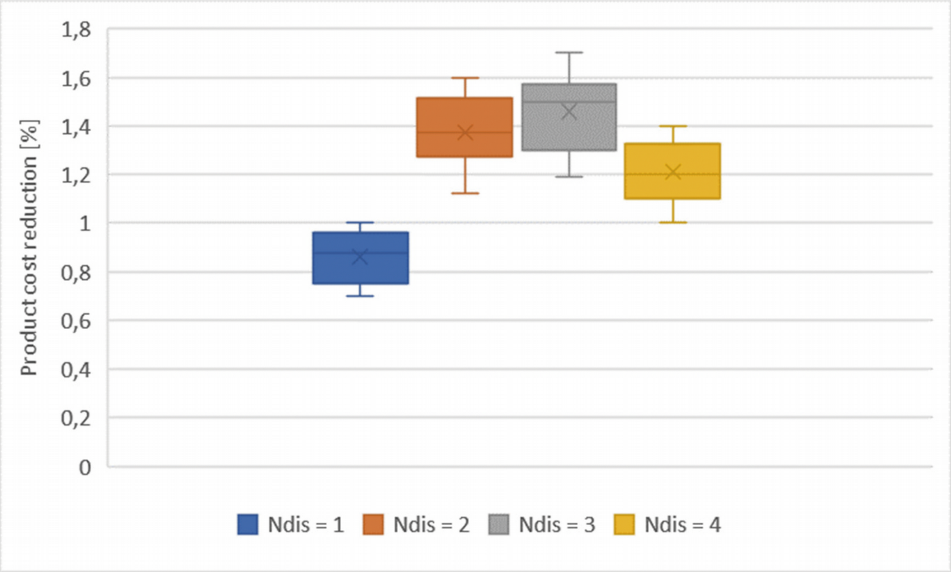


Figure 8. Box plots related to cost reduction peaks for every simulated number of operators

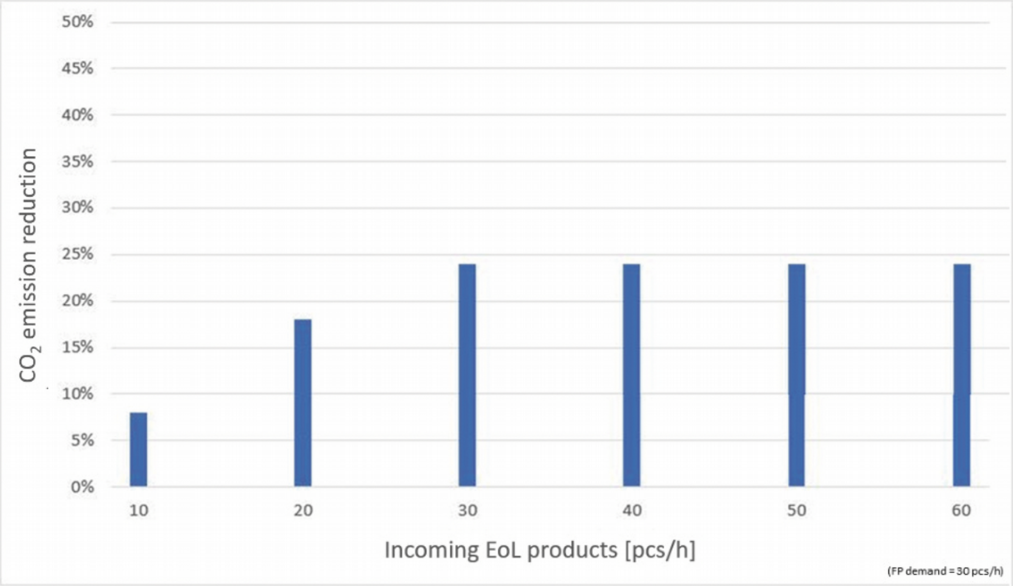


Figure 9. CO_2 emission reduction by varying the number of EoL products

For this reason, a second scenario was tested, which considered the possibility of recovering the components with the highest unit value (with reusability index Ir = 0.3): frameworks, printed circuit boards and external housing. As reported in Figure 10, a cost reduction of 1.5% was achieved with a number of inputs of 7 pcs/h (compared to 30 pcs/h in the previous scenario) and grew very quickly with the increase in the recovered EoL products, slowing down and becoming stationary at the peak of 7% cost reduction. This finding sheds light on the importance of an optimised design aimed at the disassembly process, and in particular, at the reuse and recovery of the most strategic components.

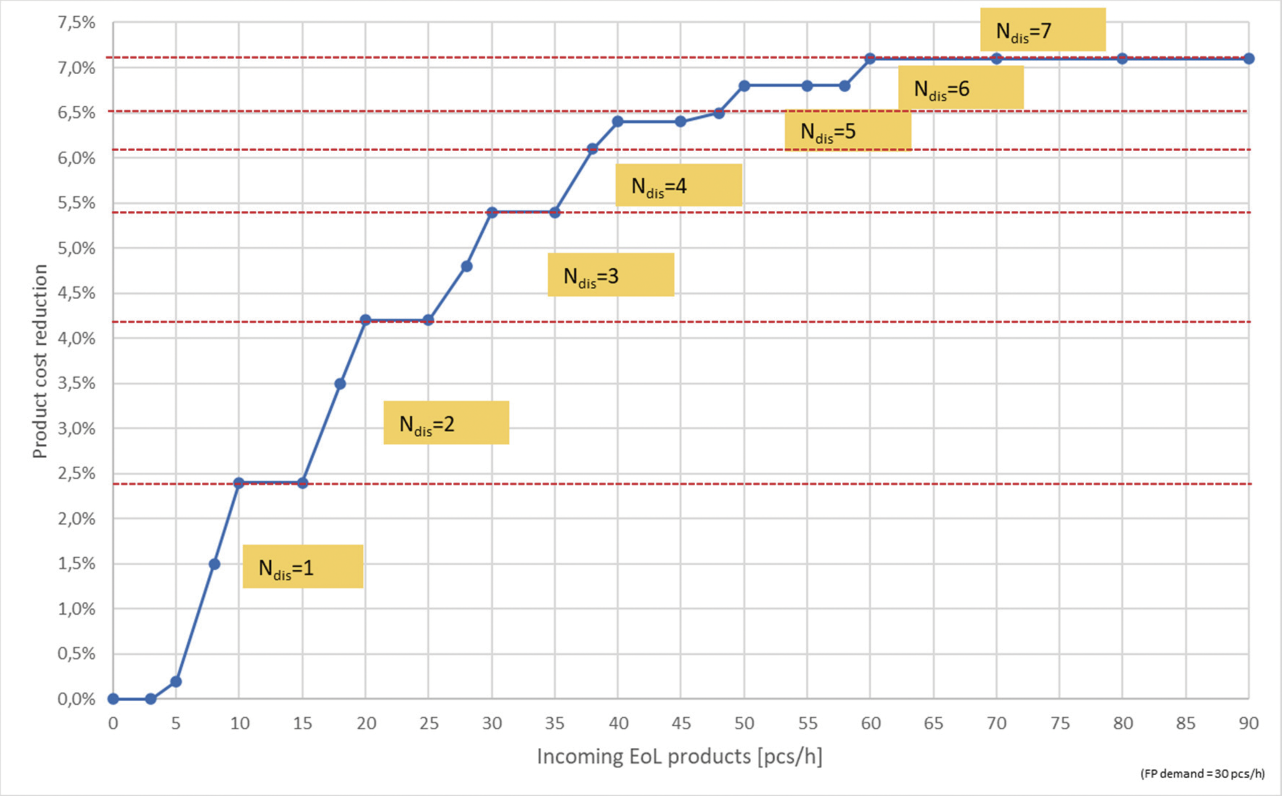


Figure 10. Scenario 2: Decreasing the product cost as a function of EoL in inputs and optimised on the number of operators

5. Conclusions and Further Steps

The approach proposed in this paper is used to assess the economic convenience of integrating a new manual disassembly line with the operating assembly processes of a traditional manufacturing plant. The proposed approach allows us to evaluate the feasibility and the economic and environmental benefits of integrating of a disassembly line within a manufacturing company. The consequent software implementation takes the variability of the input factors into account and provides the optimal number of operators necessary for the disassembly line. The implemented approach provides the following relevant data to the decision maker: (i) the impact on cost reduction by integrating a disassembly line of EoL products with assembly lines of finished products in a manufacturing plant; (ii) the necessary input (EoL) and output (finished products) flows; and (iii) the manpower required for the new disassembly line.

Two case study scenarios were tested to show the results that could be achieved through the approach application and its potentiality.

The first proposed scenario did not show significant enough improvements to justify the creation of new internal processes. The maximum improvement that was obtained was a reduction in the cost of the product by 1.5%. However, this reduction in cost made it possible to obtain a 25% reduction in CO_2 emissions, a value that certifies the importance that governments will have in economically incentivise the transition to the CE paradigm so that sustainable standards and goals can finally be achieved.

The second case showed significant decreases in terms of product cost, testifying to the fact that, by concentrating the effort towards recovering components with a high unit value, the CE processes are relevant for decreasing production costs. The highest earnings, between 6.5% and 7.5%, were achieved with a relatively high number of operators, which suggests moving part of the manpower from the assembly line to the disassembly line and vice versa to concentrate them only when the EoL flows incoming are greater, thus avoiding a surplus of workforce in periods where the need is lower.

The implementation of the model in the software environment provides several advantages. First, it forms the basis for a practical tool for stakeholders who must make decisions related to possible projects involving the management of EoL products. It also makes it possible to include random variables that cannot be taken into consideration without software implementation. The tool also allows us to study how variables such as the disassembly sequence and the plant layout influence the functioning of the system.

The proposed approach is a valid instrument to support the product design phase, which is fundamental for improving the sustainability of the manufacturing industry. In this case, the system can be powered with different possible product configurations, to predict which one allows for the optimal recovery of components from future EoL products.

Finally, the approach represents a starting point for future developments aimed at improving the system through the following:

1. *Integration of reverse logistics*: It will be necessary to estimate the reverse logistics costs, both economic and 'environmental', but it will also enable determination of the incoming flows and the state of use of the single incoming product (e.g. leasing contracts would decrease the years of product use, with a natural consequence of improving the reusability and recyclability indices and encouraging the return of products).
2. *Adding the disassembly depth optimization feature*: optimising the disassembly depth is fundamental to establishing a point in the decomposition sequence beyond which it is disadvantageous to employ manpower, and this strongly depends on the value of the components and materials downstream of the sequence. From this perspective, it is also necessary to define the disassembly sequence to be used, which can easily be investigated within the software by developing an additional function that uses all the parameters and indices already introduced in this study.
3. *Development of a virtual simulation tool*: This step presupposes the evolution in a discrete event simulator through a further in-depth study of the user's actual plant to allow system validation.

This last target will be followed by improvements in the experience of using the tool from the user's perspective, setting up automatic construction systems of the logical model according to the bill of materials of the product that must be disassembled, and automatic parameterisation using a database containing the average values usable for various components and materials.

Declaration of Conflicting Interests

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