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# A model for the economic assessment of disassembly-line integration in traditional manufacturing processes

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**Abstract**

Managing End-of-Life (EoL) products and reintroducing materials and components within the production loop become crucial for guaranteeing the Circular Economy business model. In such a way, the proper management of disassembly process for recovering components and materials from returned EoL products is essential as well as strategic: disassembly is the main gateway of information and can ensure economic returns. This paper aims to provide a model for the economic assessment of the introduction of a manual disassembly line in a traditional and already operating assembly line of manufacturing industries. Therefore, recovered components and materials could directly feed the assembly lines and the recycling processes. The model takes in input probabilistic factors, as products' characteristics, and provides the operating times and component recovery indicators, as well as allows the sizing of the right number of operators needed in the new disassembly line through the optimisation of the industrial cost. An interesting natural evolution of this study is the development of a model-based simulator, with the aim of providing a user-friendly tool to industrial practitioners to estimate the economic feasibility and convenience of introducing a disassembly line.



*Keywords:* disassembly; circular economy; manufacturing industry; end of life products; modelling; sustainability.

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## 1. Introduction and Background

The current governmental scenario pushes manufacturing industries to reach new economic, environmental and social sustainability targets and achieve smart and sustainable processes [1] [2]. Governments, industries, societies and researchers around the world made several attempts in the last years to respond to challenges of resource scarcity, environmental impact or economic benefits or combinations of these. Several efforts were conducted for rethinking various business processes for contributing to sustainable performance of manufacturing aimed at an equilibrium among economic, environmental and social dimensions of sustainability [3], [4], [5]. This is necessary for contributing to the circular economy paradigm and improving sustainable performance of industrial realities.

"*The circular economy (CE) is an economic system that emerges to oppose the linear open-ended system (produce, consume, dispose), with the aim to accomplish sustainable development, simultaneously creating environmental quality, economic prosperity and social equity to the benefit of current and future generations"* [6].

However, the literature review conducted by [7] highlighted that "CE relevant research has evolved primarily as research on waste generation, resource use and environmental impact while neglecting business and economic perspective". Instead, a systematic perspective is needed to ensure equivalent visibility of limitations of natural resources, environmental concerns as well as economic and individual business needs. This simultaneous view will prevent biased interpretations of the CE concept [7]. Indeed, the CE business model is opening new possibilities for cost and environmental impact optimisation, which will be crucial for the future survival of different types of industrial companies.

For all these reasons, the management of End-of-Life (EoL) products become an essential process that, if correctly conducted, saves resources, reduces the load of wastes destined for ecological islands or incineration and can lead to economic advantages. Choosing the best management strategies for EoL products will be an increasingly important and strategic issue for manufacturing companies [8].

Following the consolidated 3R principles of CE [9], [10], EoL products should undergo one of the following processes at the end of their life: 1) reuse of the product as it is or 2) disassembly process for recovering some components from the product (in 1) and 2) a product/some components are immediately destined for a new use, equal to the original use); 3) repair: the product's functionality is restored by replacing or repairing the damaged components; 4) disassembly and/or remanufacturing: the product is disassembled and the original components are remanufactured to improve them or create new functions or the entire product is remanufactured; 5) disassembly and recycling: the product is disassembled, achieving the components that will be re-assembled into new products or that will feed raw material production processes [11].

The best process certainly varies according to products and market characteristics, company's policies and strategies, as well as other factors, such as environmental impact, product quality, laws and regulations, etc. In any case, it is evident that disassembly is a crucial process, that could become critical if not properly managed and controlled. Disassembly is a critical process for many reasons, the key link connecting product return with product recovery, a prerequisite for other processes, and the main gateway of information [12]. For all these reasons, disassembly process should be seen from a strategic perspective in manufacturing companies in order to meet CE principles.

Indeed, to date, in literature, the disassembly process in industrial manufacturing realities meeting CE principles is studied from many perspectives, such as: methods for evaluating the disassembly times and/or the optimal sequence of disassembly [13], [14], [15]; optimisation models for collection and disassembly of EoL products [16]; the characteristics of EoL products that must be disassembled [17], therefore the design features for easier disassembly and effective recovery [18]; methods and tools for assessing disassemblability of products in order to support the implementation of re-design actions for improving product de-manufacturability and EoL performance [19]. In 2018, [20] presented a method to support a profitable disassembly line design of the post-use products, while, more recently, in 2020, a multi-scale modeling and the design of a dismantling process was proposed by [21] in order to achieve a more advanced circular economy in the heavy vehicle industry.

However, from a preliminary state-of-the-art analysis, no study provided methods or models for the assessment of the economic convenience of integrating a new disassembly line with already operating assembly processes of a manufacturing plant, considering the probabilistic parameters' effects on the economic feasibility. Therefore, this study would provide first insights through the development of a model for evaluating the feasibility as well as the economic and environmental benefit coming from the integration of a disassembly line within a manufacturing industry, taking the variability of the input factors into account and providing the optimal number of operators necessary for the disassembly line. Therefore, the disassembly line will take in input EoL products recovering components destined for reassembly or recycling. The model also provides an estimate of the CO2-eq emissions that such a system could save.

The paper is structured as follows: section 2 presents the adopted method, section 3 shows the proposed model, section 4 provides a numerical example of the model application and section 5 presents the discussions of the work and further steps of this research.

## 2. Approach

Reorganising assembly departments based on product and market characteristics, is a necessary step for properly introducing a disassembly line to recover materials. Since the reorganisation mainly involves the workforce (excluding the existence of automated disassembly processes), the approach must optimise the number of operators to be assigned to the new disassembly line and must analyse the cost-effectiveness when the factors in input change.

The approach adopted in this study is constituted of 4 main steps, listed below, and starts from the highest level of abstraction and, then, goes into detail on the individual operations:

1. The first step involves the modelling of the disassembly line, establishes the sequence of the various stations, considering possible disassembly operations that can be carried out in parallel, the distances to be covered and priority criteria on the operations, which will be adopted by the operators; moreover, the links existing with the assembly line are established.
2. The second step focuses on the calculation of disassembly times for each phase of product's disassembly, which affects the sizing of the workforce.
3. The third step aims to calculate reusability/recyclability indices. Since the EoL products are characterised by an uncertainty about the state of its components, which depends on the design characteristics and on the type of use that has been made of it, it is necessary to define the probabilities of reuse for each recovered component and the quantities that can be achieved from recycling process (dependent not only on the technological characteristic of the processes but also on the contamination to which each component was subjected).
4. Finally, the fourth step involves the definition of the economic parameters to be included in the objective functions and then the analysis of economic convenience. The outcome will be the maximum achievable reduction in production costs, and the optimal number of operators to be assigned to the new disassembly line.

## 3. A model for economic assessment

The aim of the model is to estimate how the introduction of the disassembly line influences the product cost. It must define the main technical and economic parameters that impact the analysis and provide numerical outputs which are the references to the decision-making.

The following assumptions are considered:

(i) the EoL product includes all the components of a pre-defined bill of materials;

(ii) the EoL product is not obsolete and at the end of the use phase it is still produced by manufacturing firms;

(iii) the disassembly phases are manually carried out by the operators, trained to perform all the operations;

(iv) the disassembly sequence in input is optimal;

(v) all operations and costs relating to reverse logistics for recovering EoL products are neglected.

The 4 steps of the approach were then applied for a proper and logical design of the model and the results are reported in the following subsections.

### 3.1. Modelling of the disassembly line

The system is represented by a single department in which the two assembly and disassembly lines operate in parallel. Figure 1 presents the IDEF0 scheme of the aforementioned department, as well as inputs, resources, control parameters that allow the model to generate the main outputs.

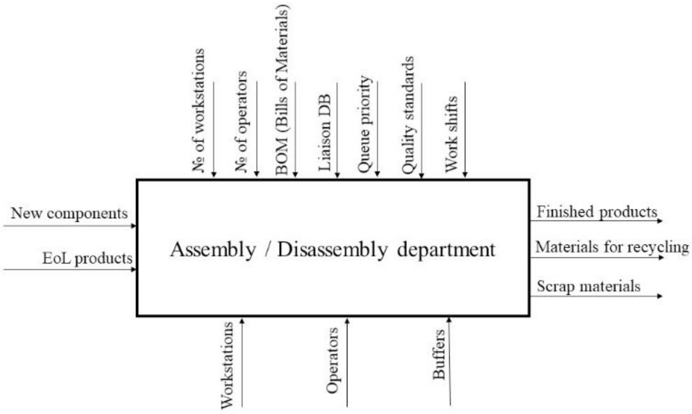


Fig. 1: IDEF0 scheme of assembly/disassembly department

In this step, the disassembly sequence is important to define the optimal order to adopt for recover components from EoL products. Therefore, EoL products enter in the line and pass through the workstations in a predetermined sequence. In each station, a specific component or sub-assembly is separated, which can be destined, according to the system parameters and the state of the piece, towards a new station, the assembly line (after treatment), recycling o disposal processes (Figure 2); instead, the remaining main structure of the EoL product is sent to the next station.

In parallel, the assembly line (Figure 3) receives the recovered components and assembles them into new products together with virgin components; in the absence of arrivals from the disassembly line, the assembly line uses components from internal production or from suppliers. Therefore, it operates independently and according to the production rate, on which depends the number of manufactured products and the number of operators assigned to assembly line.

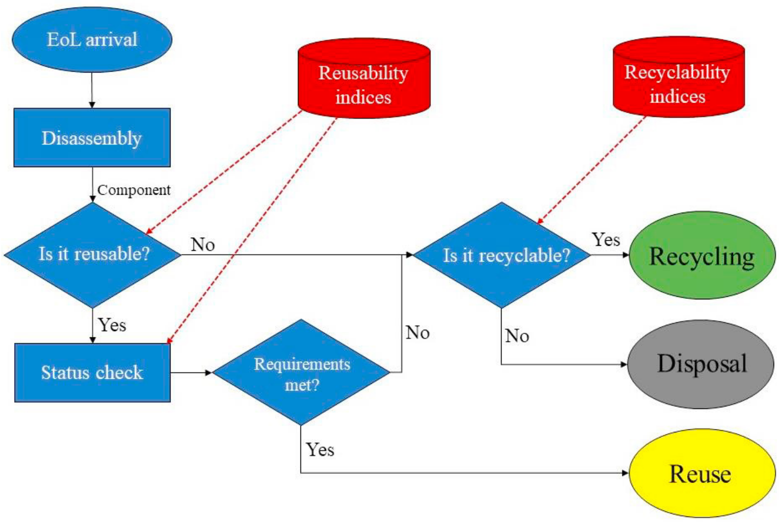


Fig. 2: Disassembly and verification process into the workstation

### 3.2. Calculation of disassembly times

The calculation of the disassembly time is essential to estimate the number of EoL products that a single operator can disassemble in a fixed period. To each disassembly phase, a time is assigned based on the specific sub-system that must be disassembled, and according to the Liaison DB [12], a database built through the collection of empirical data related to several EoL products, which contains, for each sub-assembly, the standard time needed for the separations of the components, calculated under standard mechanical conditions. This time is combined with specific corrective factors, which take the geometric characteristics (e.g. shape, length, diameter, etc.), the state of maintenance (e.g. presence of rust, deformation) and the tool used for disassembly into account. For example, the unscrewing of a screw with specific geometry and dimensions takes a certain time, which is increased if there is a high possibility of rust formation, but also if it is planned to use manual tools rather than screwdrivers electric tools.

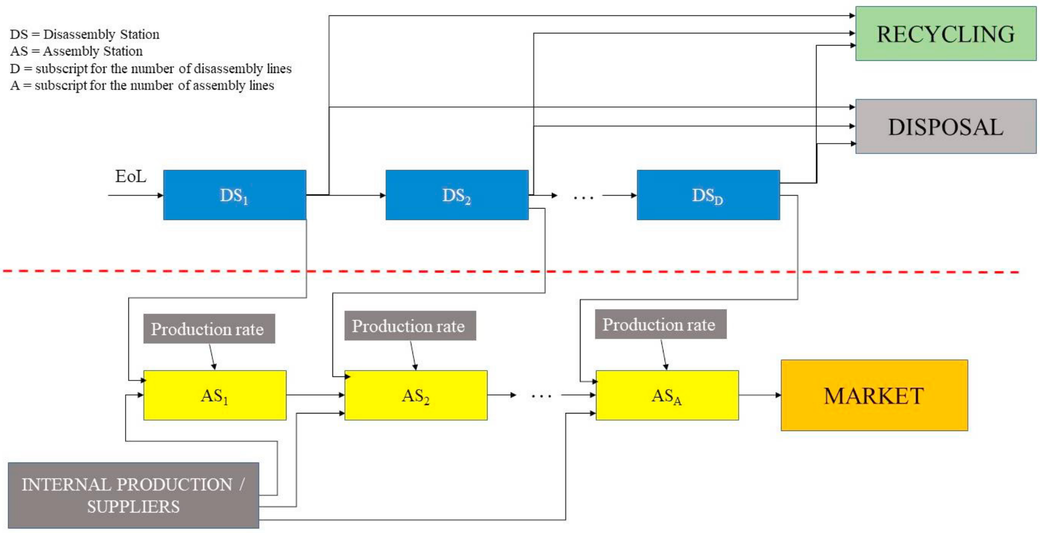


Fig. 3: Assembly/disassembly lines

After each disassembly phase from which a potentially reusable component is achieved, an additional time that the operator must dedicate to check the component compliance with quality standards has to be considered. This time must be defined on the basis of the company standards and of current regulations; moreover, this time varies according to the age of the EoL product. Anyway, this operation is essential to avoid feeding the assembly line with worn or damaged components.

### 3.3. Definition of reusability and recyclability indices

Once disassembled, the component can be reused, recycled or disposed. The model considers specific reusability and recyclability indices, respectively indicated as $I_r$ and $I_{rec}$. The first index $I_r$ is calculated only for the components designed to be partially or totally reused after small treatments and it defines the probability that the obtained component is in good condition after being broken down; the second index $I_{rec}$, calculated for each component and for each material of the component, calculates the quantity of new raw material that can be achieved from the starting material, through recycling processes [22].

Below, in the following subsections, the details of each index are provided.

#### 3.3.1 Reusability Index

The index $Ir$ (1) is given by the product of $D$ (i.e. disassembly index) and $M_D$ (i.e. material degradation index):

$$I_r = D * M_D \tag{1}$$

The *D* index considers the possibility that the component will be damaged during the decomposition. To properly estimate *D*, two parameters should be considered for each component:

1. The number of steps, n, preceding the separation of the component;
2. The total time t to separate the component (which, therefore, also takes the previous steps into account).

The index *D* will decrease when n and t will increase, according to the technical estimate conducted by academic experts in the field of EoL products management [22].

The index $M_D$ represents the probability that the use of the product by the customer has not compromised the reuse of the specific component. This index is given by the product of 3 percentage factors [22], which consider respectively:

1. Legal and technical standards constraints: we assumed that critical components must pass quality checks before reuse and this leads to a reduction in their chances of being reused;
2. physical-chemical stress;
3. bad use by the customer.

For each of these 3 factors, qualitative risk classes are identified in order to stabilise to which one the component belongs.

### *3.3.2 Recyclability Index*

The index $I_{rec}$ (2) is given by the product of 3 percentage factors, *D* (i.e. disassembly index) and *Mr* (i.e. index of depreciation) and *C* (i.e. index of contamination):

$$I_{rec} = D * M_r * C \tag{2}$$

$M_r$ is the “Material Recyclability”, an economic parameter defined as the ratio between the value of recycled material and the value of the virgin material (3):

$$M_r = \frac{V_P}{V_M} \tag{3}$$

where $V_M$ is the minimum value of the material before it is treated, $V_P$ is the value of the post-recycling material, both measured in €/kg or $/kg [23].

This index reflects different aspects and properties of the material (physical, technical, technological, economic and environmental) and provides information on the efficiency with which these resources are recovered for a new use in production process.

The index of contamination of a component *C* considers the materials with which the component is in contact during the useful life of the product, or the contaminations that could occur during the disassembly phase. Contamination leads to a reduction in the percentage of material recovered through recycling. Some plastics, for example, cannot be recycled if contaminated with other materials. The presence of contaminants, such as waste metals or dangerous substances, can preclude or make the recycling of metals economically impractical [22]. For example, to properly evaluate the factor *C*, it may be necessary to identify the surfaces covered by paints, lacquer, adhesive substances, insulators, coatings and any situation where two incompatible materials) can come into contact and become contaminated. For this index, qualitative risk classes must be defined in order to identify to which class the components of the bill of materials belongs.

### *3.4. Economic analysis*

The model minimises the objective function reported in the following equation (4), which considers the unit cost of manpower for assembly and disassembly lines, the unit cost of components (new or recovered from EoL), and the possible revenue from recycled materials (reported in the formula as a reduction of cost). Therefore, equation (4) allows to estimate the effect that the introduction of a manual disassembly line has on the unit cost of product. Then, the number of operators in charge of disassembly can be optimised by the adoption of appropriate optimisation tools. Without the consideration of the disassembly line, the unit cost of product is simply represented by the unit cost of manpower of assembly line and the unit cost of new components for the assembly process.

$$C_u(T) = \frac{C_{man}(T)+C_{comp}(T)-R_{rec}(T)}{N_{PF}(T)} \tag{4}$$

The single items of equation (4) are explained below in equations (5), (6), (7), (8), (9) and (10).

In particular, equation (5) provides the number of final products [pcs] requested by the market and processed by assembly line in the simulated period T [h], with $P_r$ [pcs/h] representing the constant production rate requested by the assembly line.

$$N_{PF}(T) = P_r * T \tag{5}$$

Equation (6) presents the manpower cost, with $N_{ass}$ e $N_{dis}$ respectively the number of assembly and disassembly operators, $c_h$ [€/h] is the hourly manpower cost, T [h] is the simulated time. Instead, equation (7) provides the cost of the components used in the assembly line, obtained by subtracting, from the cost of the needed components, the value of the parts recovered from EoL products.

$$C_{man}(T) = ((N_{ass} + N_{dis}) * c_h * T \tag{6}$$

$$C_{comp}(T) = N_{PF} * (\sum_{i=1}^{N} c_i * \alpha_i) - (\sum_{i=1}^{N} c_i * \alpha_i * X_i) \tag{7}$$

where $i$ is the index associated to the single component and $N$ the number of components; $c_i$ and $\alpha_i$ are respectively the unit cost [€/component] and the coefficient of use of the *i-th* component [component/pcs]; $X_i$ is the number that, multiplied by $\alpha_i$, returns the number of recovered components $i$ that is absorbed by the assembly line, and for this reason it cannot exceed the $N_{FP}$ value (see equation (8) below).

$$X_i = \begin{cases} \min\left\{Q_{EoL}(T) * I_{r,i},\ N_{dis} * \frac{T}{T_{dis,u}} * I_{r,i}\right\} for\ Q_{EoL}(T) * I_{r,i},\ N_{dis} * \frac{T}{T_{dis,u}} * I_{r,i} \leq N_{FP}(T) \\ N_{FP}(T) \qquad otherwhise \end{cases} \tag{8}$$

where $T_{dis,u}$ is the average time it takes an operator to completely disassemble the EoL product; $I_{r,i}$ is the reusability index for the component $i$ and $Q_{EoL}(T)$ is the quantity of EoL products that are collected and disassembled in the time interval T.

Equation (9) provides the revenue achieved from the sale of recycled materials. Inside the formula, *M* includes all the materials of the bills of materials; $m_{i,j}$ [kg/component] represents the quantity of material *j* of the component *i*; $I_{rec,i,j}$ is the recyclability index of the material *j* of the component *i*; $p_j$ is the price of the *j-th* material [€/kg]; and $c_{r,j}$ is the cost of recycling [€/kg] of the *j-th* material.

$$R_{rec}(T) = Z * \sum_{i=1}^{N}\sum_{j=1}^{M}(m_{i,j} * \alpha_i * I_{rec,i,j} * \left(1 - I_{r,i}\right) * (p_j - c_{r,j})) \tag{9}$$

$$\text{with } Z = \min\left\{Q_{EoL}, N_{dis} * \frac{T}{T_{dis,u}}\right\} \tag{10}$$

*3.5. Estimation of CO2-eq avoided*

Since the recovery of components leads to the need to produce less, while recycling process allows to obtain new raw material from waste by exploiting more ecological processes respect to primary production, the model estimates the reduction of the environmental impact in terms of CO2-eq avoided. This is a secondary function, which does not influence the economic analysis. The estimation of the environmental impact is carried out through the $\delta_{GWP}$ index $[kg_{CO2-eq}/kg]$, which measures the difference in terms of CO2-eq emissions between the production of material from virgin sources and recycled materials (11).

$$\delta_{GWP,m} = Y_{GWP,m} - Y'_{GWP,m} \tag{11}$$

where $Y_{GWP,m}$ $[kg_{CO2-eq}/kg]$ and $Y'_{GWP,m}$ $[kg_{CO2-eq}/kg]$ (GWP stands for Global Warming Potential) represent, respectively, the quantity of CO2-eq emitted for producing 1 kg of material m from virgin and recycled materials. The indices $\delta_{GWP}$ are tabulated for different types of materials in 22.

Plastics have variable values: some (such as PE-HD, PS and PET) present values higher than 80%, comparable to metals; other plastics (such as polycarbonate) have lower values, mainly due to the performance of recycling technologies.

The reduction of carbon dioxide emissions occurs both through reuse and through recycling. The first contribution of the formula (12) refers to the components recovered for reusing, for which it was considered the CO2-eq that would have been emitted for processing the virgin materials ($Y_{GWP,m}$), of which the components are made, that instead is avoided thanks to the reuse. The second contribution refers to the components intended for recycling, which are broken down, when possible, into the masses of different materials, of which the components are made, used to produce new raw materials. In this second term, the CO2-eq avoided thanks to the recycling process corresponds to $\delta_{GWP}$. Therefore, the total saving of CO2-eq (expressed in kg of CO2-eq) is given by the following formula (12), which provides the contributions given respectively by the reuse and recycling activities:

$$Saving_{CO2-eq} = \sum_{i=1}^{N}\sum_{j=1}^{M}\left(\alpha_i * m_{i,j} * X_i * I_{r,i} * Y_{GWP,j}\right) + Z * \sum_{i=1}^{N}\sum_{j=1}^{M}\left(\alpha_i * m_{i,j} * I_{rec,i,j} * \left(1 - I_{r,i}\right) * \delta_{GWP,j}\right) \tag{12}$$

For quantifying the CO2-eq savings in the case of reuse, only the emissions concerning the processes to achieve the quantity of raw material are considered, while the pollution due to the transformation of raw materials into the final components is not considered.

## 4. A numerical example of model application

Below, a simple example of the model application. Suppose we want to evaluate the economic convenience of the disassembly of a generic product P, consisting of 3 components A, B and C which are separated into three consecutive steps and then sent to the assembly line or recycling process. The main data of the case study are provided in Table 1.

Table 1. Case data

| Components | | | | | Reusability | | | Composition | | | Reciclability | | | CO2-eq | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | α | Cost (€/u) | $T_{dis}$ (s) | Step | D% | $M_d$ % | $I_r$% | Material | Mass (kg) | (p – c) €/kg | C% | $M_r$% | $I_{rec}$ % | $Y_{GWP}$ ($kg_{CO2\,eq}$/kg) | $\delta_{GWP}$ ($kg_{CO2eq}$/kg) |
| A | 1 | 2 | 250 | 1 | 100 | 75 | 75 | Polypropilene | 0,2 | 0,6 | 75 | 81 | 61 | 2,33 | 1,22 |
| B | 1 | 1 | 130 | 2 | 100 | 100 | 100 | Aluminium | 0,1 | 1,3 | 100 | 100 | 100 | 9,67 | 9,17 |
| C | 2 | 5 | 180 | 3 | 75 | 50 | 38 | Steel | 0,5 | 0,3 | 100 | 98 | 74 | 2,98 | 2,16 |
| | | | | | | | | Copper | 0,2 | 1,5 | 75 | 100 | 56 | 3,2 | 2,76 |

In addition, the following information:
$T = 960$ h, $Q_{EOL}(T) = 10000$ pcs, $N_{PF}(T) = 20000$ pcs, $N_{ass} = 3$, $C_h = 10$ €/h.
From equation (4) using the data in the table, it is possible to optimize $C_{u,Ndis}(T)$ as a function of the number of operators involved in the disassembly line. The following values are achieved:

$$C_{u,0} = 14{,}45\ €/u \ \ , \ C_{u,1}(T) = 12{,}81\ €/pz \ \ C_{u,2}(T) = 12{,}10\ €/u \ C_{u,3}(T) = 12{,}57\ €/u$$

which highlight the economic advantage obtained with the maximum cost reduction of 17%, reachable with 2 operators.
Finally, the amount of CO2-eq saved is estimated through (12): $Saving_{CO2-eq} = 32456\ kg\ CO_{2-eq}$

## 5. Discussion and further research

The main contribution of this research work is the proposal of a model as a first step to evaluate the convenience of introducing disassembly processes in an existing manufacturing plant. Indeed, although in the current literature the issues related to the disassembly process in industrial manufacturing are addressed from many perspectives in order to meet the circular economy principles, no study presented a generic model, suitable for several types of companies, for the assessment of the economic feasibility of integrating a new disassembly line with assembly processes of a manufacturing system. The proposed model allows to: define the characteristics of the product and of the assembly/disassembly lines thanks to a high level of system parameterisation, becoming suitable for different manufacturing realities; optimise the number of operators of the disassembly line according to the expected EoL arrivals and the production rate; provide first insights on the environmental benefit through the estimation of the reduction of CO2-eq emissions and the positive economic impact for society. Therefore, the proposed model will allow to increase the awareness of manufacturing companies respect to the environmental and economic convenience of recovering their own EoL products and introducing disassembly lines within the manufacturing system.

The proposed model is a good basis for the development of a decision support system, focused on the industrial cost of the product, that can help industrialists and practitioners to establish the economic convenience of introducing a new disassembly line in a manufacturing plant.

However, the model presents some limitations, which could become further developments of this study:

- the recyclability and reusability indices are hard to estimate without a very careful technical study. User experience or expert advice could be decisive in this context, where small variations on the parameters can lead to big differences on the results;
- logistics management and related costs, which could be far from negligible, are not integrated;
- the static operating times do not realistically describe processes whose inputs (EoL) have irregular characteristics due to their use;
- the environmental analysis does not consider the emissions generated by the means of transport needed for the transportation of EoL products, nor the possible need of the company to store supplies to make up the uncertainty of the arrivals.

However, several further steps were already outlined. First of all, the model can be implemented in several simulation software or optimisation algorithms can be adopted for finding optimal solutions. In this last case, the disassembly line becomes a “black box” and elements that could be relevant are neglected, such as the priority criteria and the formation of bottlenecks; instead, through the implementation in simulation software, the possible diversified scenarios can be simulated, results closer to reality can be obtained, the virtual environment of the manufacturing lines can be showed shedding light on possible bottlenecks. Moreover, this will facilitate the management of the large number of variables and would favour the logical division into individual workstations. The future tool could include the integration of reverse logistic costs and should consider variable times characterised by probability distributions: pursuing these goals is necessary to achieve results as closer as possible to reality. Through the integration of additional cost parameters linked to EoL return (the current version of the model implies a spontaneous EoL return, a situation that not always is true) and the use of random variables of time for a proper representation of the disassembly processes, the tool will be closer to industrial realities. Finally, a further interesting step will be the application of the model in industrial contexts, with the aim of evaluating in different case scenarios.

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