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Integrating environmental assessment in the assembly line design process

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Abstract:

This study focuses on including the environmental assessment of a process in its design. Two improvement targets can be considered to optimize the environmental efficiency of a production phase: a cleaner process, and the optimization of the assembly of the different product parts. This work makes it possible to apply life cycle assessment to product industrialization, and specifically to assembly lines. The reduction of the environmental impacts (EI) of the production phase can be achieved by modeling the assembly line and/or optimizing equipment choices and organization. To accomplish this, we developed a tool. In this tool, equipment EI are calculated using two databases: i) an equipment database, listing equipment characteristics: lifetime, EI for individual functional units and use parameters; and ii) a consumption database, listing the consumables and energy EI. A comparison of the equipment EI is carried out for the same function, use conditions and functional unit. Equipment is then selected according to its EI. Finally, the tool determines the EI of the optimized assembly line.

Keywords: **design process, environmental assessment, assembly line**

Glossary

β: consumption coefficient of equipment
i_{Eq}: EI of equipment for a specific functional unit
I_{Eq}: EI equipment for the functional unit of assembly line
I_{Input}: Impact of input
$i_{Manu,Eq}$: EI of manufacturing phase of equipment for a specific functional unit
$I_{Manu,Eq}$: EI of manufacturing phase of equipment for the functional unit of assembly line
$i_{Use,Eq}$: EI of use phase of equipment for a specific functional unit
$I_{Use,\mathrm{Eq}}$: EI of use phase of equipment for the functional unit of assembly line
L_{AL}: Lifetime of assembly line
L_{Eq}: Lifetime of equipment
n_{Input}: Amount of input
n_{Eq}: Amount of equipment
V_P: Average value of parameter “p”
$V_{p,h}$: Value of parameter p for the processing of the product “h”
$\%_{Prod,h}$: Ratio of production of the product “h”

1 Introduction

Standards ISO:14001 (for environmental management systems), and ISO:14040 and 14062 (for life cycle assessment and the eco-design approach) help manufacturers to reduce their environmental impacts (EI). Since 2011, standard ISO:14006 has defined the guidelines to link these three standards, involving the quality approach (ISO:9001). The current concern of manufacturers is to improve the performances of their manufacturing systems with respect to business objectives and environmental regulations. The environmental efficiency of a product’s production phase can be improved through new, cleaner processes and through assembly optimization.

On one hand, life cycle assessment (LCA) [1, 2] is one of the most well-recognized environmental assessment methods. The LCA method focuses on the product (or process) and on the infrastructure required to make, maintain, and dispose of it. Nevertheless, LCA does not link the environmental consequences of design parameters. On the other hand, current design methods (e.g. discrete event simulation) do not measure the environmental performances of the manufacturing process.

In this context, Azapagic *et al*. [3] have described how LCA can support decision-makers in process industries. Nevertheless, De Benedetto *et al.* [4] highlight LCA's limitations during strategic decision-making based on an environmental mapping strategy. In the past ten years, certain studies have combined environmental assessment with the design process in various fields. For example, Berlin *et al.* [5, 6] developed a method to test alternative dairy productions to minimize wasting milk. Bojarski [7] studied incorporating the LCA approach into maleic anhydride production supply chain modeling. Other authors combine LCA with performance manufacturing assessment systems. They investigate the recycling strategies for plastic waste [8] or predict the environmental impacts of various urban water management strategies [9]. Wohlgemuth *et al.* [10] and Reinhard *et al.* [11] used a method combining discrete event simulation with ecological material flow analysis for motor fabrication. They include economic factors (bottleneck detection, maintenance planning and machine purchasing) and ecological factors (emissions, raw material and energy consumption). Other authors have developed a model focusing on only one impact category indicator, energy consumption, in two industrial sectors: manufacturing [12], and vehicle assembly [13].

In this framework, this article focuses on including environmental assessment in decision-making during design. Today, many state-of-the-art studies examine the LCA of built-in and operational processes. The specificity of our tool is that it enables assessment of the assembly line EI via LCA in the initial design phases. The first objective of the tool is to determine and compare the EI of equipment with the same function and used in the same conditions. The ultimate objective is to determine the optimum improvement strategies by selecting the best equipment alternative and the best equipment organization, taking environmental decisions into account with multiple, conflicting objectives (technical, economic, etc.). This article describes a method used to determine and compare the EI of assembly line equipment, and it does not describe equipment LCA in detail.

2 Scope of the LCA used in the tool

Assembly line LCA does not require detailed modeling: scheduling tasks, parallel tasks, prioritization of operations. Nevertheless, all of the assembly line and support activity equipment must be listed. This tool is focused on the assembly line manufacturing and use phases. Figure 1 illustrates the production process and the scope of the LCA study (black dotted line). The energy and consumables for production are taken into account. The products are eliminated from the study (raw materials, finished products, production scrap, etc.). For the assembly line, the distribution phase EI is considered to be negligible. Due to a lack of data, the assembly line end-of-life is not included in the scope.

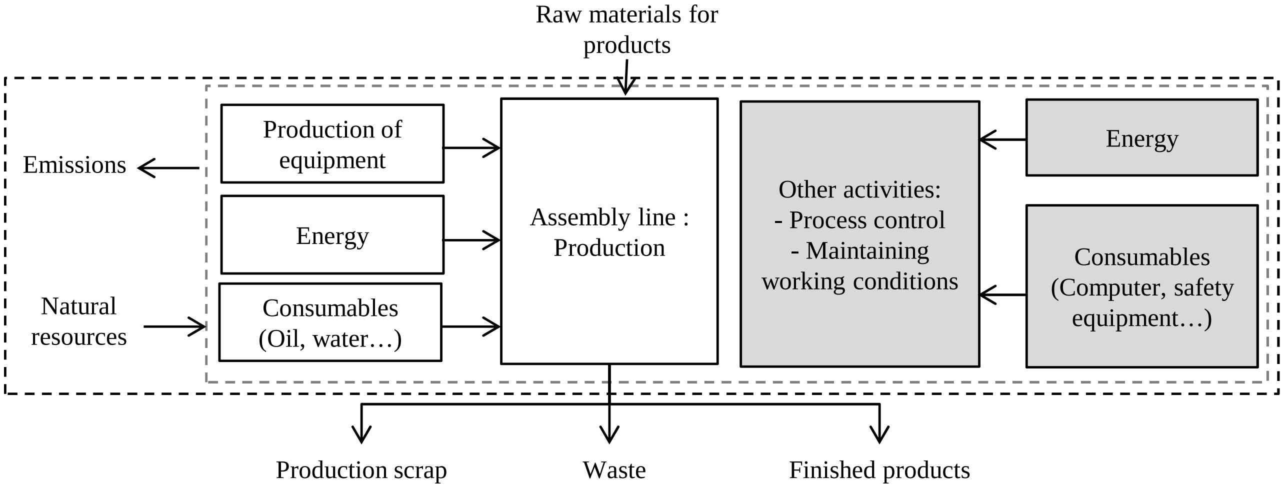

FIG. 1 – Diagram of the manufacturing process and scope of tool (black dotted line)

3 Method to calculate assembly line environmental impacts

In the tool, only three phases are considered: raw material extraction, manufacturing and use. Nevertheless, the material modules in LCA software databases (e.g. the Ecoinvent database) include the transport between the first two phases. To assess EI, LCA studies of vehicle assembly lines take into account two indicator categories: global warming and non-renewable energy [14-17]. In agreement with the Bojarski study [7], vehicle assembly line LCA [18] highlights significant EI of two additional indicator categories: respiratory effects and terrestrial ecotoxicity. Therefore, our tool considers these four environmental indicators: global warming, non-renewable resources, respiratory effects and terrestrial ecotoxicity.

First, the tool determines the equipment EI for a specific functional unit. This functional unit takes into account the equipment function, the number of products processed, the equipment lifetime (e.g.: X product load for Y years). Users can study the effect of equipment and product line usage conditions on the EI of one type of equipment. Then, the tool calculates the equipment EI for the same functional unit as this one for the assembly line (for the assembly line lifetime, for the same number of products assembled, etc. e.g.: allowing the production of X cars for Y years). In this case, equipment with the same function can be compared.

To determine the equipment EI for a specific functional unit (i_{Eq}), the manufacturing phase EI and use phase EI are separated (1). The manufacturing phase EI ($i_{Manu,Eq}$) are the sum of the raw material extraction and equipment manufacturing EI. The use phase EI are related to equipment inputs (consumables and energy): their impacts (I_{Input}) and their amount (n_{Input}) (2). The input amounts change according to use conditions. Therefore, $i_{Use,Eq}$ must be determined for each "equipment/use conditions" pair.

$$i_{Eq} = i_{Manu,Eq} + i_{Use,Eq} \tag{1}$$

$$i_{Use,Eq} = \sum(n_{Input}.\ I_{Input}) \tag{2}$$

Then, to compare and select the best equipment, the EI must be calculated for a same functional unit (I_{Eq}): the assembly line functional unit. As previously, the manufacturing phase EI ($I_{Manu,Eq}$) and use phase EI ($I_{Use,Eq}$) are separated. In this case, $I_{Manu,Eq}$ depends on $i_{Manu,Eq}$ and the number of equipment replacements (n_{Eq}) during the assembly line lifetime. n_{Eq} is equal to the ratio of the assembly line lifetime (L_{AL}) over that of the equipment in use conditions (L_{Eq}) (3). In some cases, equipment lifetime is constant regardless of the use conditions. In other cases, the lifetime depends on use parameters (use time, number of uses).

$$I_{Manu,Eq} = i_{Manu,Eq}.n_{Eq} = i_{Manu,Eq}.L_{AL} / L_{Eq} \tag{3}$$

To determine $I_{Use,Eq}$, the product profile and use conditions must be taken into account. The first query is the average value of parameter "p" (V_P) as a function of product profile (4): weighted by the product production rate h ($\%_{Prod,h}$). The parameters are practical (e.g.: number of prints, number of screws, use time, etc.). $V_{P,h}$ is the value of parameter "p" for product "h".

$$\mathrm{V_P} = \Sigma_{Prod,h}(V_{p,h}.\%_{Prod,h}) \tag{4}$$

Then the consumption coefficient (β) must be taken into account to determine the mean consumption value of the "equipment/use conditions" pair from the parameter value. Thus, the value of $I_{Use,Eq}$ is calculated using equation (5).

$$I_{Use,Eq} = \Sigma(\mathrm{V_P}.\ I_{Input}\ .\ \beta) \tag{5}$$

Finally, the assembly line EI (I_{AL}) can be determined. Assembly line consumption can be expressed by the equipment consumption: energy or consumables. Thus, the assembly line EI can be related to the assembly line equipment impacts (6).

$$I_{AL} = \sum I_{Eq} = \sum(I_{Manu,Eq} + I_{Use,Eq}) \tag{6}$$

4 Organization of the tool

The tool is built in Access software. In the tool, the assembly line is considered as a succession of workstations. Each workstation is characterized by certain functions and equipment (Figure 2). Five equipment rules are highlighted: transfer, assembly, loading/unloading, process control and maintaining working conditions (lighting, heating, safety equipment).

As in previous studies [6, 19], the EI values for equipment manufacturing or inputs are not calculated in the tool but taken from two environmental databases: "equipment database" and "consumption database". As previously explained, the EI of four indicator categories are recorded in these databases: respiratory effects, global warming, non-renewable resources and terrestrial ecotoxicity.

Figure 3 illustrates the organization of the data in the tool and their links. The "equipment database" lists all of the equipment and its characteristics (e.g.: picture, name, lifetime, and manufacturing EI). The comparison of equipment with the same function requires recording alternative types of equipment. The "consumption database" collects all the equipment inputs (several energy mixes, compressed air, sheets of paper, oil, etc.)

and their EI. To model the assembly line, the user must describe some characteristics i) of the assembly line (e.g.: lifetime, functional unit, product line), and ii) of the product line (e.g.: name, product use rate). To add equipment, the user must define its function and check the value of its use parameters (optional).

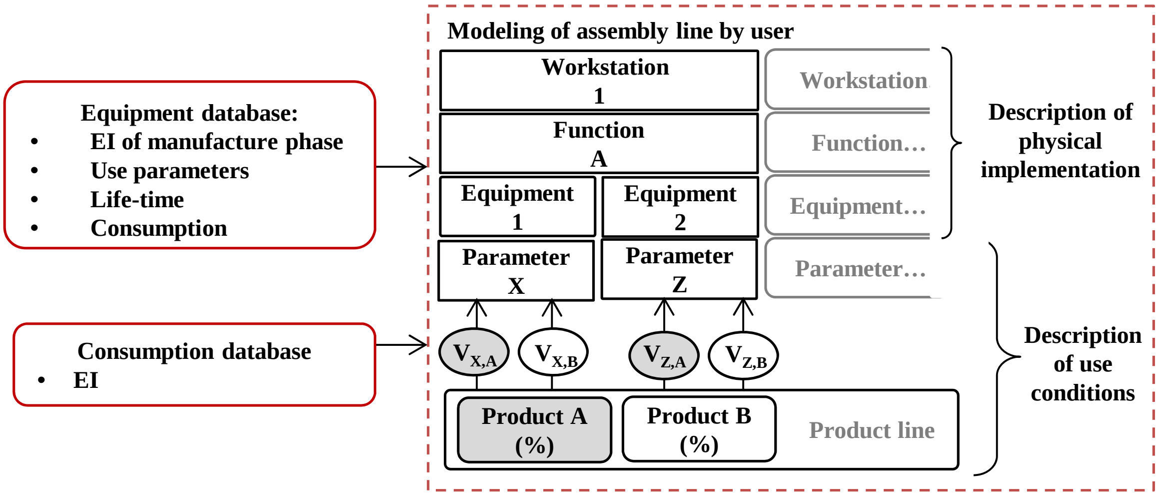

FIG. 2 – Organization of the tool

To determine equipment EI from use parameters, the tool links the characteristics of the equipment (lifetime, parameter values) and the use conditions (workstation, product line) (Figure 3).

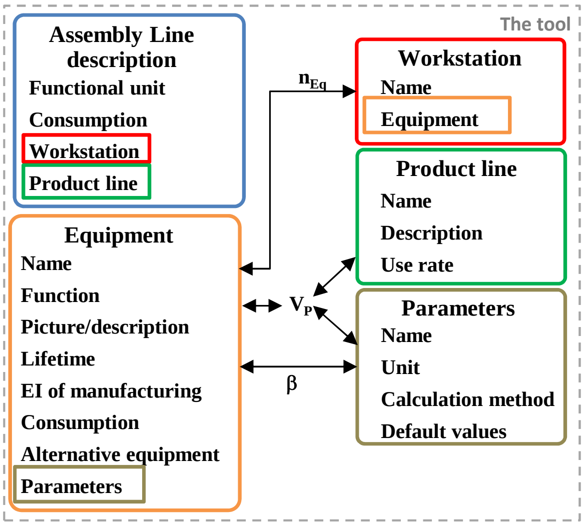

FIG. 3 – Organization of data and links between characteristics

5 Optimizing environmental impacts during the design phase

Figure 4 illustrates the method used to optimize the assembly line EI thanks to an informed choice of equipment. The performance of the tool depends on a large equipment database.

The user chooses the equipment, defines its function and its use parameters (workstation and product line). The tool determines the EI of the equipment and the EI of all alternative equipment with the same function (and for the same functional unit). Figure 5 illustrates the results of a comparison of two wrenches. In this case, the tool was used to model a section of a truck assembly line, composed of 77 elements of equipment. The assembly line functional unit is: processing 150 trucks per year for 25 years. i_{Eq} was determined using Simapro software and the IMPACT2002+ method, and the Ecoinvent database was used.

The user can then compare the equipment EI and select the best alternative in view of the economic, technical and environmental constraints. To optimize assembly activities with respect to EI, the user can observe the effects of modifying the amount, use parameters or equipment distribution. Finally, the tool determines the assembly line EI. In addition, the tool indicates an EI ratio for a function, workstation, or equipment within the total value of each indicator category, as illustrated in Figure 6.a. As shown in Figure 6.b, the tool can separate the EI of the manufacturing phase and the use phase. The results in Figure 6 were generated by the study of one section of a truck assembly line, composed of 77 elements of equipment.

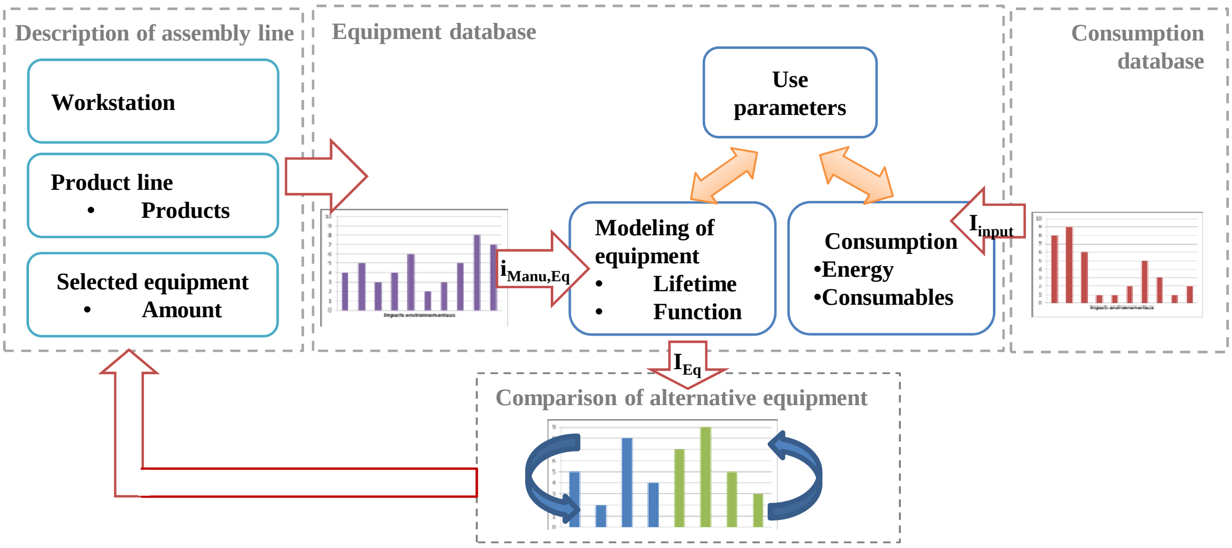

FIG. 4 – Selection of equipment according to its environmental properties

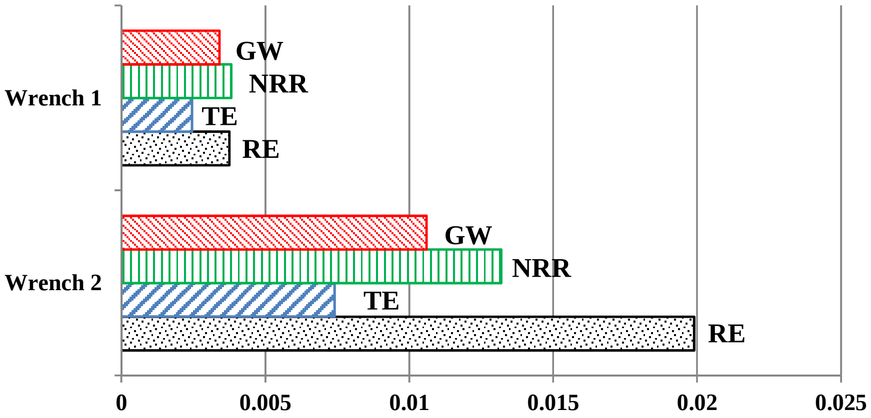

FIG. 5 – Comparison of normalized EI for two wrenches for the same functional unit (GW: global warming, NRR: non-renewable resources, TE: terrestrial ecotoxicity and RE: respiratory effects).

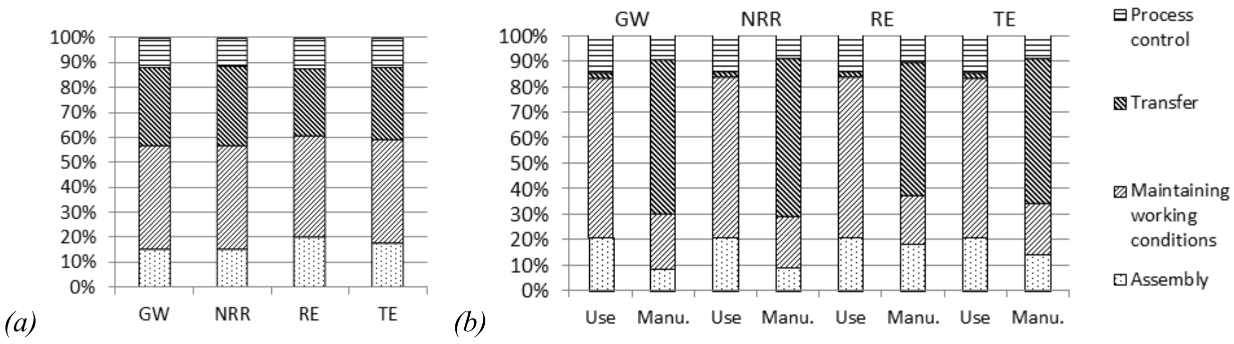

FIG. 6 – Proportion of each assembly line function in the overall assembly line EI (a); in the EI of the use. phase and manufacturing phase (b). (GW: global warming, NRR: non-renewable resources, TE: terrestrial ecotoxicity and RE: respiratory effects).

6 Conclusion

Many studies focus on the LCA of a process after its design. Contrary to these studies, this tool makes it possible to assess the assembly line EI in its initial design phase. The user can model the assembly line and determine its EI, and also modify equipment quantity and distribution. The user can thereby optimize assembly line EI by comparing and selecting equipment (and an organization) with less EI.

Thanks to the modeling results, this tool makes it possible to identify the workstation, function or equipment with higher consumption and/or EI. Users can then search for new equipment with the same function or a new process with less environmental impacts.

Currently this tool only concerns the manufacturing and use phases of an assembly line. To improve tool accuracy, the entire assembly line life cycle should be taken into account. Therefore, the "Equipment database" must be improved to allow recording of new data and new links. To improve tool performance, more equipment must be analyzed using LCA and recorded in the "Equipment database".

To go further, the EI could be converted into monetary values. For example, a carbon tax is used in certain countries, with the aim to limit and control emissions in air, water and soil. A spot market regulates the price of one ton of CO_2 produced. This tool should therefore be modified to take this parameter into account.

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