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TRIZ based computer aided LCA for Ecodesign

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ABSTRACT
With the growing environmental conscience, the focus of sustainability has shifted from environmental assessment to improvement. An increasing number of improvement tools are being developed, but they all lack integration with the assessment phase, or provide very simplified and unreliable assessment tools. We propose an integrated approach to environmental assessment and improvement, with a focus on green product development and problem solving. The main novelty of this work lies in the adoption of TRIZ (Theory of Inventive Problem Solving) fundamentals, which allow us to transform traditional LCA criticalities, i.e. the most impacting flows of a product, into eco improvement criticalities, i.e. the potential of improvement of each flow. For this, we developed a graphical ontology that guides the designer in mapping the product life cycle, identifying and highlighting criticalities, and tracking the improvement effort. A new approach is proposed, focused toward problem solving rather than environmental certification. Indeed, available systems fail to highlight the contradictions that normally occur during problem solving, in which any improvement is met with a trade-off that is never fully understood until a new assessment is performed. In the proposed methodology, the mapping scheme is designed to help problem solving, by graphically highlighting the critical product components that need to be improved, suggesting customized guidelines that target specific flows and life cycle phases, and foreseeing possible trade-offs that may arise.

KEYWORDS
LCA; TRIZ; infographics; eco-improvement; green design; decision making

1. Introduction

Ecodesign comprises a set of tools for assessment and improvement of environmental impacts. Assessment tools, among which Life Cycle Analysis (LCA) is by far the most common, aim at determining the environmental impact of a product. Improvement tools aim at improving the most critical areas of a product life cycle, by modifying the product or the manufacturing process characteristics, in order to reduce the overall environmental impact. To achieve a more sustainable product, eco-improvement tools rely on LCA software to identify the most critical areas of a product life cycle. Therefore, an eco-improvement tool is only as good as the underlying life cycle analysis of the product. However, the complexity of an LCA requires a standalone software that rarely allows an integrated eco-improvement phase. Examples of this approach are the well know GaBi (www.gabi-software.com) and SimaPro (www.simapro.com) software. On the other hand, eco-improvement tools often offer an integrated assessment phase that is necessarily simplified and often imprecise. Attempts at a structured approach to both assessment and improvement [4], [5] often focus all effort on the improvement phase, integrating problem solving tools like TRIZ (*Theory of inventive problem solving*) [2], [16], without realizing that the assessment phase should be tailored to the needs of product development, both regarding analysis time and level of detail. CAD software has also tried to integrate Ecodesign tools in recent years [3], [6]. The main benefit is the structured approach to product modeling of CAD software, which allows a greatly reduced inventory building time. Unfortunately, the LCA is overly simplified and the results are unreliable for a real LCA perspective [7], beyond a mere indication of the most impacting components.

The bridge between assessment and improvement tools is represented by the results of the LCA analysis; more specifically, how they are displayed and interpreted [8], [17]. While raw data is the heart and soul of LCA software, post-processing of the results is often lacking [4]. In recent years, the focus has being shifting from database development to results evaluation [9]. Life Cycle Mapping (LCM), often based on Sankey diagrams [8], [10], [14], has become the norm, for both inventory building and environmental impact tracking. Mapping a product life cycle is a convenient way to help the user in keeping

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track of the huge amount of data required for a LCA, but it is especially useful in giving a detailed and graphical depiction of the environmental impact. However, life cycle mapping is still in its infant state. Interactivity is limited and often lacks the ability to map complex products [10]. Furthermore, available mapping systems have not yet achieved their true potential; to be not only a graphical representation of a product impacts, but the way to track the entire improvement effort.

This paper addresses the need for an integrated approach to environmental assessment and improvement, especially designed for product development and problem solving. The proposed methodology offers:

- A data collection scheme. Through the use of materials and processes databases, it is possible to help the user in gathering raw inventory data and effectively reducing the time required to build a Life Cycle Inventory (LCI).
- A multi-level approach to Life Cycle Mapping. Thanks to a multi-level approach to LCM, a designer can map complex products or processes without choosing between detail and readability.
- An inventory reduction scheme. Thanks to a highly aggregated and abridged LCA, the user can focus on the most relevant product components, disregarding irrelevant areas of the life cycle, in order to reduce the time required to complete a Life Cycle Inventory.
- A criticalities identification scheme. Product criticalities are identified and highlighted, based on the LCA results, by applying a set of problem solving principles derived from the TRIZ methodology.
- A criticalities ranking scheme. Product criticalities are ranked across multiple performance indicators, to give a final aggregated ranking.
- An integrated selection of eco-improvement guidelines. Thanks to very specific and flow dependent guidelines, the user will be able to access a set of improvement guidelines directly from the mapping system.
- A visualization of possible eco-improvement trade-offs. The most common improvement trade-offs are tracked and displayed directly on the mapping system.
- A comparison of different product configurations. Different product configurations can be compared by juxtaposing the results of a change in product or process characteristics.

2. i-Tree methodology

The proposed life cycle mapping module is part of a comprehensive Eco design suite called i-Tree [11], which is being developed by the University of Bergamo. i-Tree supports the designer during product development, by assessing environmental impacts and providing effective tools to address such impacts, improving the original product, while ensuring structural and functional requirements. The methodology is structured along three phases: the inventory phase that comprises data collection and process mapping; the impact phase that assesses the environmental impacts and determines the criticalities of the product or process; and the improvement phase that guides the designer along the improvement effort.

2.1. Inventory phase

The workflow is centered around the mapping module. All material and energy flows of the product life cycle are entered directly on a diagram called the Inventory Map (Fig. 1), which has been conceived by merging IDEF0 modelling and infographics. The Inventory Map is the detailed life cycle of the product. It comprises all the manufacturing processes and all the materials necessary to produce, use and dispose of the final product. It is, in essence, the description of the product entire life. A good deal of effort has been spent to differentiate by colors and graphics the different kinds of flows (input-output materials, energy, wastes, material loops), in order to provide a concise overview of what has been collected and what functional unit has been chosen. Figure 1 depicts an exemplary production process, where incoming resources are transformed in the final product. Boxes represent each sub-process; blue flows represent material resources; orange flows represent the energy consumption of the sub-process; and red flows represent auxiliary materials needed for each sub-process. New inputs are identified by triangles of the same color scheme, while wasted resources outflowing from each sub-process are identified by a black triangle.

However, info graphics are not simply a visualization tool, but rather a new way to build the inventory. The graphical ontology we propose helps the user keep track of the type of flow and of the aggregation and disaggregation of flows along the production process. In fact, the mapping system allows to quickly aggregate and disaggregate flows creating a different inventory each time. This has a significant effect especially during the improvement phase, where flows are ranked based on their criticality. By combining different flows in a single one, the final ranking shifts to a new configuration. For instance, if the user were to combine a set of similar flows, each of little impact (e.g. the energy absorbed by each tracking-motor in a solar power plant), the final ranking would show this new combined flow as a high impacting one, and point the designer towards its improvement. Tracking how flows are combined is essential in defining the most critical components of a product or process.

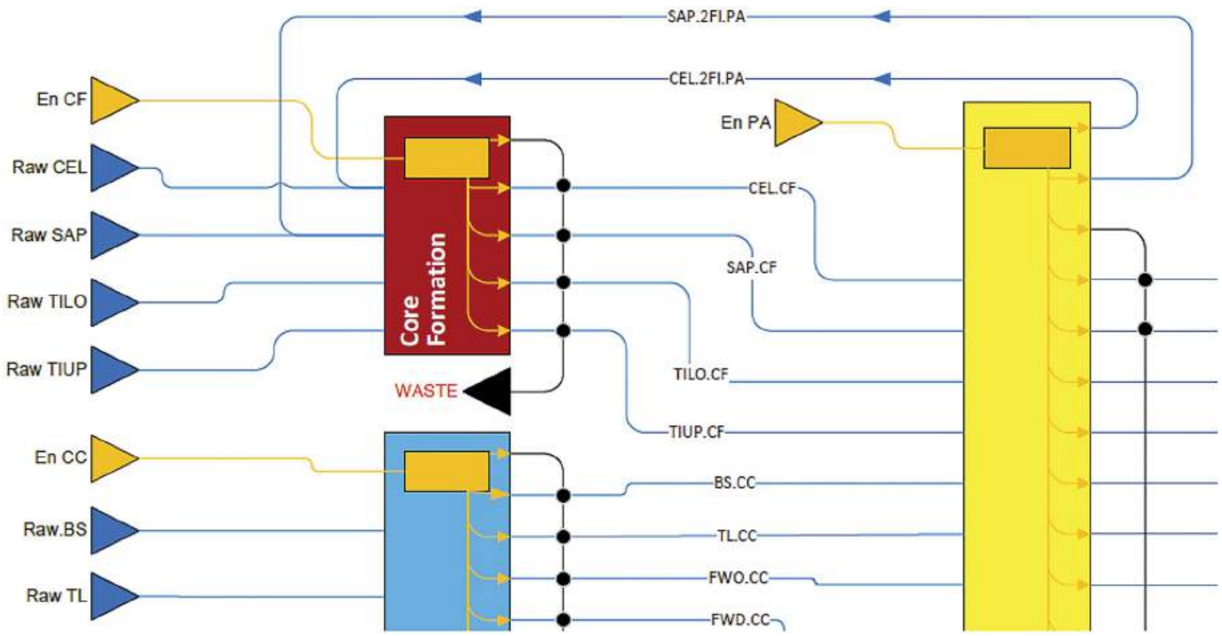

Figure 1. Inventory map.

Further addictions include a data collection scheme (2.1.1) to reduce the time required for data collection, a multi-level approach (2.1.2) to map complex products and processes, and an inventory reduction scheme (2.1.3) to focus the designer data collection and mapping effort towards the most significant areas of the product life cycle.

2.1.1. Data collection scheme

One of the most difficult and time-consuming tasks of a Life Cycle Analysis is the gathering of all necessary data. The user needs to know all material quantities involved in the manufacturing and functioning of the product, all wastes produced and energy consumed by each manufacturing process, as well as all relevant information on shipment, distribution, use, and disposal of the product. This is by all means a daunting task that usually results in either outsourcing the study to a professional LCA company, or in excessive approximation and loss of detail. i-Tree aims at providing the designer with the means to integrate partial knowledge about energy and auxiliary materials consumption, through a database of materials and processes. For each manufacturing phase where data is missing, the user will have the option of supplying just the primary material type and quantity, and at least one primary manufacturing process. The Inventory Map will show these areas as *database-entries*, highlighting their significant approximation with respect to the rest of the inventory, and i-Tree will automatically determine a combined environmental impact, based on material and process indexes. For all intensive purposes, these areas of the inventory are treated as standard components, much as fasteners, wires, and minor electrical components are commonly assessed simply by their weight or number, without detailing every sub-process required for their manufacture. The only difference is how i-Tree dynamically determines the environmental index, by combining material and process data.

2.1.2. Multi-level approach to inventory and impact mapping of complex products

Complex products featuring hundreds of components cannot be captured in a single map; the density of material and energy flows would make it unreadable to the user, and keeping track of data would be increasingly difficult. The same can be said for complex manufacturing processes, involving different stages and sub-processes. The proposed life cycle mapping methodology features a multi-level approach, applicable to either product or process mapping, that allows the designer to effectively build and analyze complex inventories. As the map levels go deeper, more detailed information is given, while shrinking the scope of the life cycle to a single manufacturing process or operation (Fig. 3).

Three levels have been defined so far:

- The lowest, third level, is the actual Life Cycle Inventory, where raw data about material and energy consumption can be found. Primary and secondary manufacturing processes make up the nodes of the map, while flows represent single materials and the energy consumption of each process. For example, the third

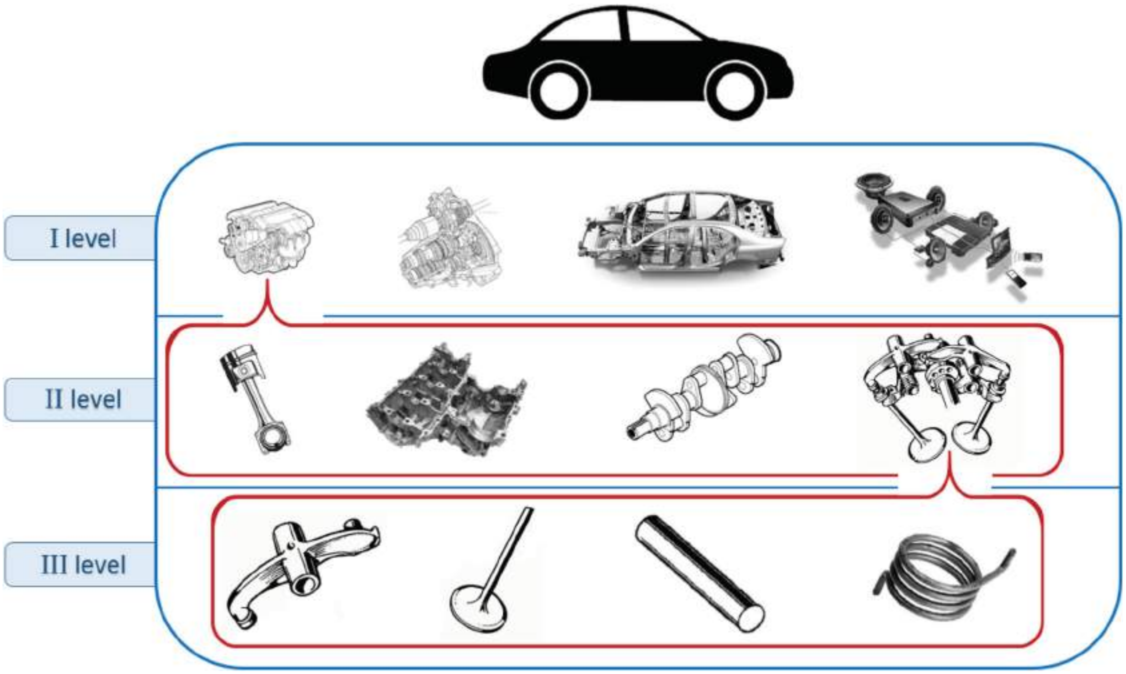

Figure 2. Example of a multilevel inventory for a complex product.

level of the crankcase (Fig. 2) would show a series of metal forming processes for the outer metal shell and all the processes required to manufacture the gaskets. This third level holds the highest detail and is the one where LCA is performed. Results are then carried up through the levels by combining material and energy environmental impact into a single aggregated flow.

- The intermediate level is often optional and should be used only for very complex systems. Its main function is to help in managing the transition of data from the lowest level to the topmost, especially when there are intra-level material loops (e.g. a cooling liquid that is reused, at a higher temperature, in a different phase of the manufacturing process). The second level shows the main processes and components of each first level sub-assembly. For example, the second level map of the engine (Fig. 2) features the crankcase, the piston assembly, the crankshaft, and the valves assembly as the nodes of the map. The map flows, on the other hand, would be the components of the third level, where materials and energy have been aggregated in a single indicator. Thus, for a set level of the map, lower level components are treated like *standard components* (electrical wires, metal sheets, fasteners) would be treated in a classical LCA; by aggregating in a single index the materials and the entire production chain.
- The topmost level gives a broad view of the entire life cycle. Flows and processes represent sub-assemblies that make up the entire product. The map nodes are the first level subassemblies (the engine, the frame, etc.), while flows depict the components of the second level.

Maps are organized in a parent-child relationship and the leveling is dynamic, to the extent that the user may apply the same logic of the three levels to any number of levels. As a rule of thumb, the designer should start building from the topmost level, identifying the main product subcomponents, and then build as few lower levels as possible, finding the correct balance between level of detail and complexity of the mapping scheme. Case studies have shown that three levels of inventory can successfully map a process of more than 500 manufacturing stages. Clearly, as the map detail rises through the levels, the map also branches into sub-maps for each component and part of the product. However, the raw data for the LCA is mostly confined to the lowest level of the inventory; thus, the designer needs to fill in each detail of only the lowest level. Higher levels are more automated. Since each level is linked to the one below through flows and nodes, the designer needs only to associate all components of a lower level to the nodes of the higher one. i-Tree will then be able to automatically map each higher level by combining the results of lower ones.

This systematic approach allows the designer to zoom in on areas of the life cycle to access more detailed information, while retaining an overall clear view of the entire product. This multi-level approach is especially important for the eco-improvement phase. Once the LCA

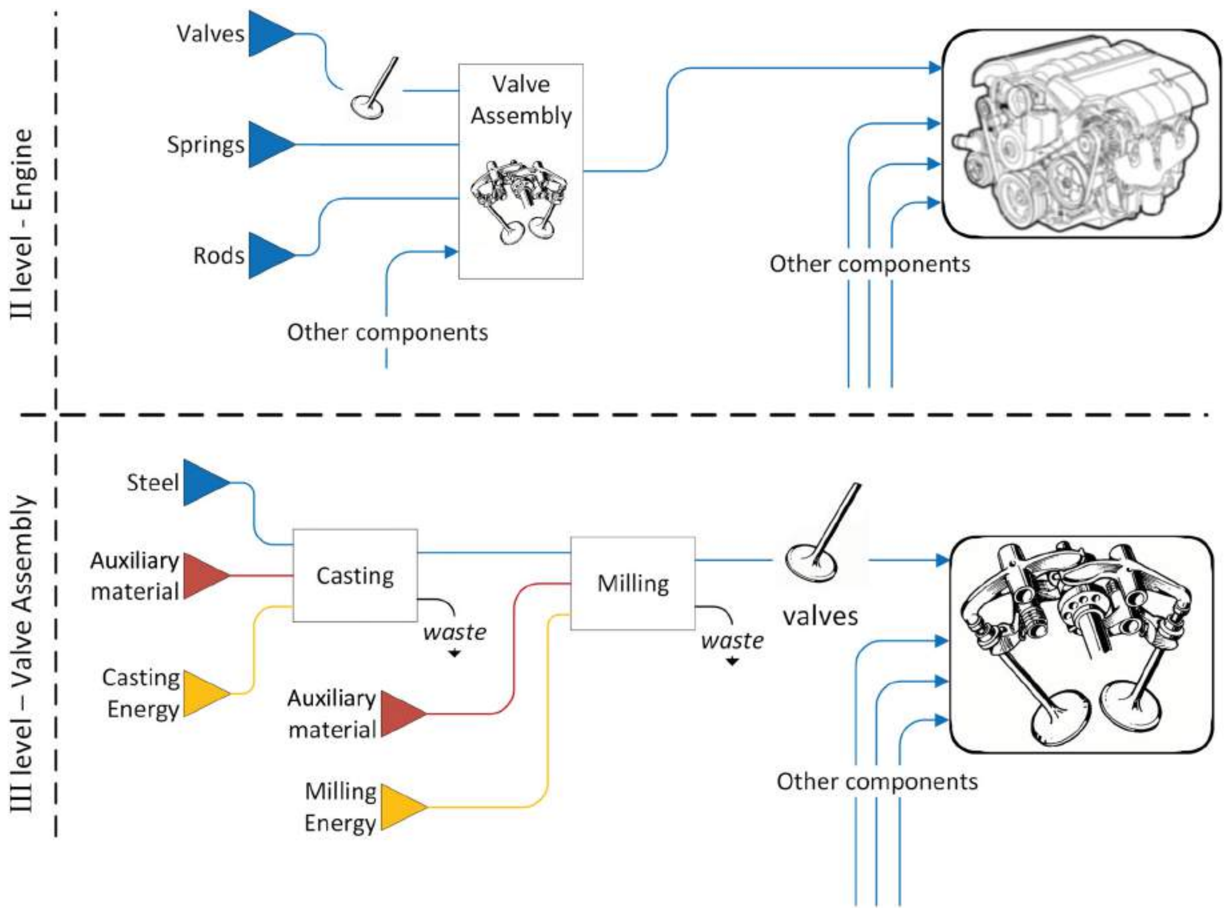

Figure 3. Multi-level approach to inventory and impact mapping of complex products. In the higher level (above) the valve flow collects all the energies and materials that have been mapped on the lower level.

results are mapped, the topmost level enables the designer to focus the improvement effort on the most impacting components, and, if possible, disregard entire sections or even phases of the life cycle. In the example of the car, the LCA might show that the use phase is by far the most impacting, on account of the fuel consumption of the car. The designer might then focus her/his attention on the components which affect the use phase the most. By zooming deeper into the levels, the same logic applies, guiding the user towards the most critical areas. The lowest level is where the improvement action is contextualized, and where problem solving tools should be applied. The eco-guidelines described in the following section can be accessed at this level.

2.1.3. Inventory reduction scheme

As aforementioned, the deeper the levels of the LCA inventory, the more maps the user will have to build. However, not all products and processes, and not all Life Cycle Analysis, require such a level of detail for every component, and time could be saved, by knowing in advance what components should be mapped in detail. For instance, the user could be able to increase the detail to a third level map of only a fraction of the second level components, if s/he had any way of knowing their relative environmental importance. The dilemma is not an easy one, as the relative importance of each component is a result of the very analysis we wish to trim. The solution we propose is the most logical approach: a preemptive and abridged study to evaluate summarily each component contribution to the overall product impact. To do so, i-Tree uses the same criteria of the *database-entries* described in paragraph 2.1.1. The user will need to supply a list of the primary materials quantity, and at least one primary manufacturing process for each component. i-Tree will then compute an aggregated index for each, and present the user with a pie-chart graph of the environmental relevance of each component. Clearly, this is by no means a substitute for the complete LCA, it is merely intended as an aid for a faster and more efficient inventory compilation. By highlighting critical areas of the product or process before the mapping procedure, the user will have a clear picture of what components should be mapped in detail, and what components have a comparatively meaningless impact and can, therefore, be approximated with *database-entries*. Thanks to this procedure, a complex inventory of hundreds of maps can often be reduced to just a few tens. Furthermore, life cycle phases can be weighted in the same manner, leading to the possibility of focusing on important phases, or even disregarding unimportant ones.

2.2. Impact phase

Although Life Cycle Inventory and Analysis are not separate entities (in fact a life cycle analysis is continuously performed, with the option to shift from the Inventory Map to the Impact Map at any stage during the Life Cycle Inventory), we identify the impact phase as the end of the inventory data collection, and the beginning of results evaluation. The Impact Map (Fig. 4) is the real heart of the procedure. Once the product or process impacts have been assessed through a standard Life Cycle Analysis based on the ISO 14040 standard for environmental assessment, the Impact Map will constantly update through every change in the life cycle, allowing the designer to develop the product while keeping track of the environmental impact. Furthermore, the Impact Map will guide the designer during the identification of critical areas of the life cycle, and during the entire improvement procedure, as explained in detail in the next section.

The Impact Map can show a number of indicators for both environmental impact (CO_2, SO_2, PO_4, etc ...), energy consumption (both renewable and not-renewable), manufacturing costs, and labor costs. Regardless of the chosen indicator, the map will highlight the relevance of each material or energy flow by changing the thickness of every line according to the flow relative contribution (Fig. 4).

2.2.1. Identification of criticalities for problem solving

Life cycle criticalities are often confused with the relative impact of each flow. Our Impact Map was born to support designers, rather than for environmental certification. Just like a Sankey diagram, it shows the relative environmental impact of each material and energy flow through the thickness of each line; i.e. the most impacting component will display the thickest line. While this is an important information, it does not show the improvement potential behind each flow. In many instances, the most impacting component is vital to the product function and has already achieved a high degree of efficiency. For example, the LCA of the production of textile fabric for the fashion industry will no doubt depict the highest environmental impact for the fabric itself. This impact is mainly due to the huge quantities of fabric being manufactured, but it cannot be reduced beyond a certain value because it is itself the product to be sold. An effort to redesign such a process could be misplaced if targeted at reducing the most impacting flow (the fabric of the example) without considering the improvement potential to be gained by such an effort. It is therefore imperative to discriminate between LCA criticalities, i.e. how impacting each flow is with respect to the overall impact, and eco-improvement criticalities, i.e. an estimation of how much

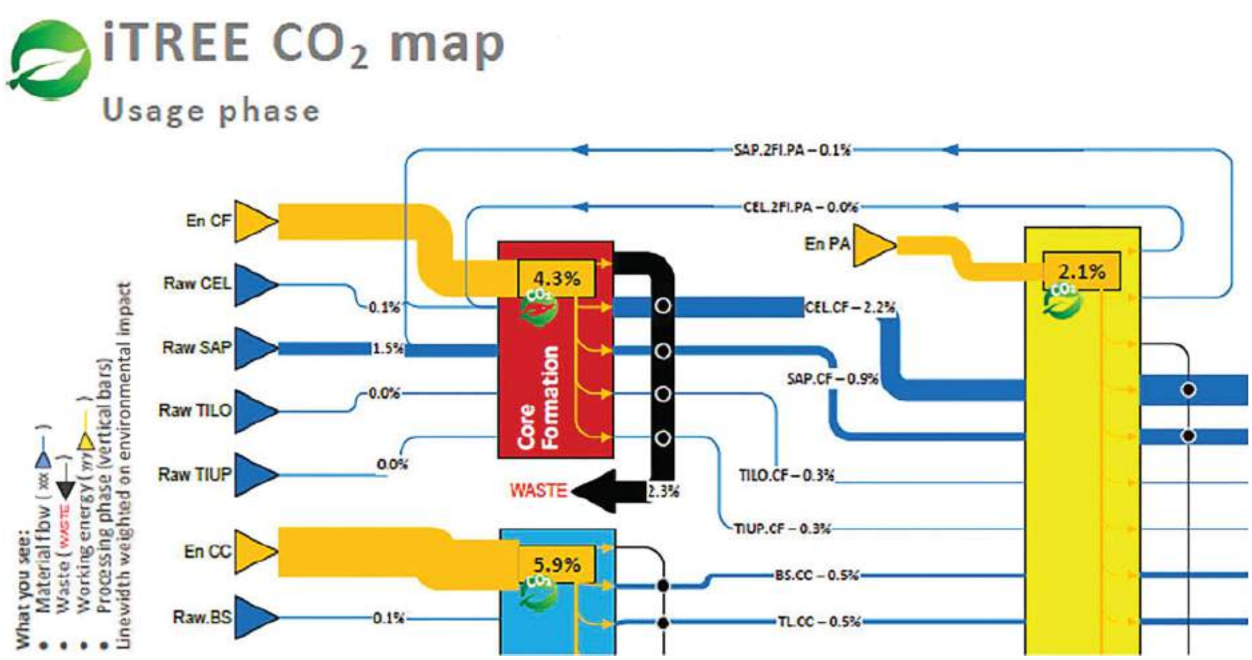

Figure 4. CO_2 Impact Map, showing the relative impact of each flow through the thickness of each line.

environmental impact can be saved for each flow. Neither of this information should be disregarded and neither should be valued alone. LCA criticalities are essential to define the environmental performance of the product. Eco-improvement criticalities should instead guide the improvement effort towards the direction of least resistance where the most benefit may be gained with the least effort.

To show the improvement potential of each material and energy flow, we propose a criticalities identification module, based on resource optimization techniques and problem solving principles like TRIZ Ideal Final Result (IFR), and a material and process selection scheme [15]. TRIZ IFR is used to identify the theoretical ideal result of each flow. For instance, the ideal result of the fabric flow from the previous example is the final amount of cloth which will in fact become wearable clothing. By subtracting this amount from the LCA results, the designer can highlight the inefficiencies of the process by mapping the quantity of fabric which is wasted during the process, and can therefore be theoretically saved. The same can be applied to energy flows: the IFR of a casting process is the theoretical energy required to heat and melt a lump of metal the size of the final part, with a unitary efficiency for both energy and material consumption. Clearly these are two straight forward examples that do little justice at the intricacy of assessing the improvement potential. For an industrial process, most material and energy flows can be assessed based on the resources and energy required to achieve the final product with zero waste production. It is therefore possible to gauge the improvement potential of the process by analyzing the product in its market-ready form. On the contrary, when studying the improvement potential of a product there is no base reference, because the improvement is gained by redesigning the product itself. It is thus much harder to gauge the improvement potential of its material and energy flows without actually redesigning the product in a new form. In this case, the improvement potential can only be a measure of the efficiency of the manufacturing process.

IFR alone gives an idea of the available range of improvement, but it is deeply affected by the choice of process and material. To account for a change in either, we propose a material and manufacturing process selection scheme, based on a materials and processes database, which guides the user in selecting a range of compatible materials and processes. Based on this selection, the designer will be able to identify the ideal choice for both. Clearly, this is still a theoretical result, as it does not account for all the interdependencies of the product life cycle, but it is merely a way to define the ideal result for both material and process selection. Furthermore, this stage should not be confused with the actual improvement phase. The idea behind the criticalities identification module is not to find greener solutions, but rather to gauge the range of available improvement, based on the efficiency of the product or process under study. It is a very raw analysis, designed to focus the designer improvement efforts where there is a chance of highest benefit.

By combining IFR with a database search of the compatible alternatives in material and manufacturing processes, i-Tree can create a new map called the Criticalities Map, where each flow thickness is a measure of its theoretical improvement range. The Criticalities Map will be the center of the improvement phase, allowing the user to interact with each flow, and tracking every change to the product or process. The total percentage of potential improvement and a final rank of criticalities are shown directly on the map in a dedicated infographics template (Fig. 4).

2.3. Improvement phase

The Criticalities Map is thought to be a highly interactive environment where the designer should be able to access a set of visualization and improvement tools. The user will be guided in the improvement of the product, and will be able to track and anticipate the effect of any change in the life cycle, as well as compare different product configurations.

The improvement phase is centered around a set of guidelines, derived from the TRIZ theory of problem solving applied to eco-design. These guidelines are very specific to the type of flow and life cycle phase that the user wishes to improve. This specificity allows for an unprecedented degree of applicability, as well as the possibility to foresee both positive and negative effects of the chosen improvement action. It is thus possible to graphically show the lifecycle areas affected by the chosen guideline and improvement tool, and foresee the typical trade-offs that characterize eco improvement. Finally, the proposed graphical scheme allows to compare the reference product or process with the improved version, to show not only the overall improvement, but also how each area of the life cycle was affected.

2.3.1. Criticalities ranking scheme

When developing or improving a product, tracking a single environmental indicator is rarely sufficient [1],[18]. In fact, trade-offs between different environmental indicators are the norm. Furthermore, costs and energy consumption can rarely be neglected. i-Tree can determine all of these, and more, from a single life cycle inventory, but, while the user can visualize each one in turn, there's a need to identify product criticalities across the entire

Table 1. Flows ranking across multiple performance criteria.

Name	Description	Eq. CO_2 kg	€	Energy MJ	Rank
Flow1	Description of Flow1	52430	22514	2,05E + 06	1
Flow2	Description of Flow2	33698	14587	8,44E + 05	2
Flow3	Description of Flow3	31403	13485	1,54E + 06	3
Flow4	Description of Flow4	26578	8507	3,02E + 06	4
Flow5	Description of Flow5	26636	11427	9,59E + 05	5
Flow6	Description of Flow6	26856	11532	3,52E + 05	6
Flow7	Description of Flow7	23726	10188	1,88E + 06	7
Flow8	Description of Flow8	12236	3990	2,32E + 06	8

range of indicators. To achieve such a result, i-Tree provides the user with a ranking of all material and energy flows across a chosen sub-set of available indicators. The ranking (Tab. 1) can be determined via a point system (based on the ranking of each flow for each of the indicators) or through a weighting system, if the user wishes to provide different weights based on the perceived importance of each indicator. The resulting ranking should be the starting point for the improvement of the product or process.

2.3.2. Integrated selection of eco-improvement guidelines

i-Tree LCM module sets itself apart from available LCM solutions, as it is not simply a visualization tool, but rather a highly interactive environment. The designer can interact with the map by focusing on any material or energy flow. This brings up a set of flow specific guidelines that suggest ways and tools to improve the environmental impact of the chosen flow. Such eco-guidelines come from the Ecomap module [13]; typical suggestions are the use of CAE software, material and process selection tools, TRIZ principles and resources, and optimization tools. They are very specific to the type of flow and the life cycle phase from which the flow was selected. Different guidelines address the improvement of different types of flow, and each guideline is tailored to the specific LCA phase where the flow stems. For instance, if the user were to select an energy flow from the use phase, one of the resulting guidelines would be "*Replace continuous action with periodic or pulsating actions and then with resonant action. Use action only when really needed (start and stop)*". Guidelines also provide relevant case studies and examples to help the user in applying the suggested tools and design principles. Sub-modules have been developed for mass reduction, through topological optimization [12], and material change, through a parametric factorial approach [15].

About 80 guidelines have been developed so far. The goal will be a set of modular guidelines, which will be created ad hoc around the selected flow, by combining: the action goal, the guideline scope, the proposed solution, the proposed tool to achieve such an improvement, and all relevant case studies and examples. This prevents the use of generic suggestions, and narrows the scope of the proposed action.

2.3.3. Visualization of possible eco-improvement trade-off areas

While simplified versions of LCA have managed to support the designer with environmental data during product development, it is yet impossible to map and keep track of all life cycle interdependencies. Modifying a single flow usually involves a series of repercussions along the entire life cycle; more so, when we act on one of the first phases, like manufacturing and pre-manufacturing. These repercussions are usually a mix of positive and negative effects. Thus, it is imperative to keep track and anticipate the major trade-offs that the designer will encounter. This is made possible by i-Tree's very specific guidelines that allow foreseeing possible tradeoffs arising from the considered action; be it reducing the product mass or changing one of the materials. Trade-offs are defined in the same way a modular guideline would be, by tracking what kind of flow the user wishes to improve, and the chosen means to improve it. A module, called i-Tree Influence [11], is being developed to track all possible trade-offs. Once the designer has chosen a guideline, s/he will be prompted to assess one or more possible negative effects that may arise from the use of said guideline. In [11] we proposed a way to foresee these tradeoffs by building a database of the effects associated with the eco improvement guidelines. This effects database was conceived on the principle that every improvement tool suggested by the guidelines has some inherent mechanism for which it is possible to foresee the outcome. For instance, when using structural optimization to reduce product mass, the result is liable to be more difficult to manufacture. Hence, the user would be prompted to think about manufacturability during product design. There are typically more than one negative effects. For example, changing the manufacturing process of a component may result in a worsening of: process energy consumption, auxiliary material consumption, raw material consumption, and product life span. Based on her/his experience with the product under development, the user may discard non-relevant effects and focus on the most pertinent ones, or s/he may wish to keep track of all trade-offs. To achieve this, we developed a simple graphical way to highlight the life cycle flows most likely to be affected by the proposed product or process change. This graphical representation of possible trade-offs is accessible directly from the impact map, after choosing a flow to modify and a relative guideline. Possible trade-offs highlight the affected areas by fading the rest of the product life cycle (Fig. 5). The material and energy flows,

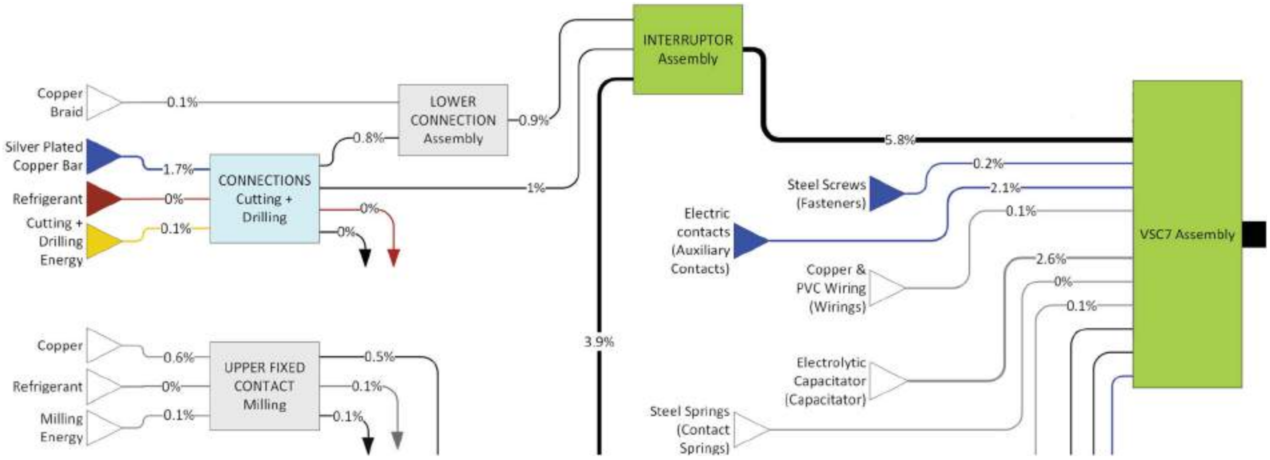

Figure 5. Visualization of possible eco-improvement trade-off areas.

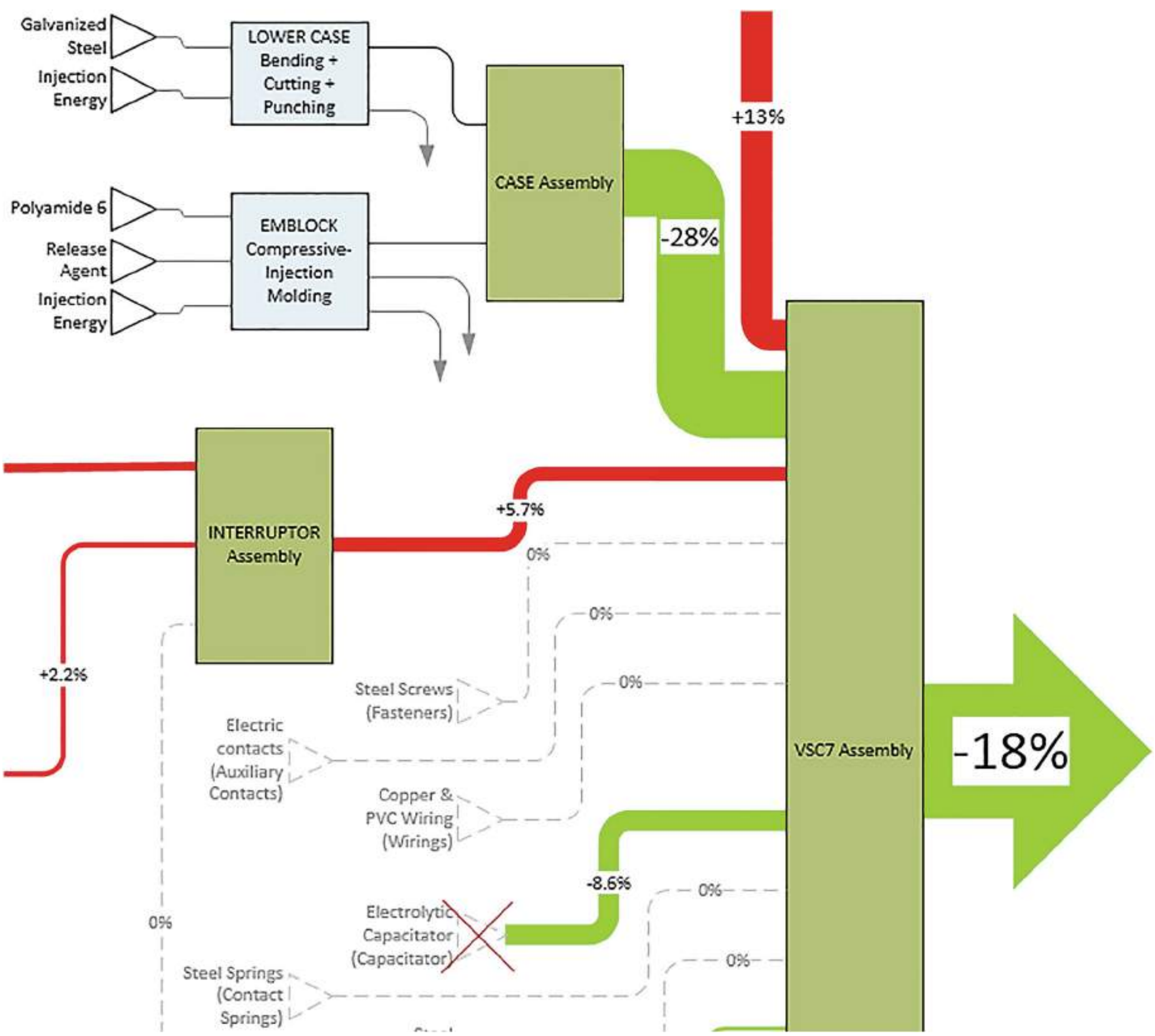

Figure 6. Comparison of different product configurations.

and the processes that remain colored on the map represent the areas most likely to be affected by the chosen improvement method.

2.3.4. Different product solutions comparison

Finally, no Ecodesign project would be complete without a comparison between the starting product and the modified version. For this, the overall environmental impact (or the overall value of any indicator, for that matter) is seldom enough. A vital information is a way to track both positive and negative effects of the new solution to understand not only the overall improvement, but also how each area of the life cycle was affected.

i-Tree provides an option which allows the user to superimpose two different LCA and visualize the net result of overlapping flows (Fig. 6). The value of each flow is the difference in environmental impact between the compared products (shown as a percentage of the total environmental impact in Fig. 6), where one is chosen as the reference product, and the other as the new product version. Flows that result in zero change are grayed out, and components that have been eliminated are strike-through. Green lines depict positive effects, while red lines represent negative effects. Thus, if the overall result is a green line, the new product version is more eco-friendly than the starting product, and vice versa.

Clearly, this scheme works best for comparing similar products, where most of the life cycle overlaps. This is, however, the most common case in product design.

3. Conclusions

This paper has addressed the need for an integrated approach to environmental assessment and improvement, especially designed for product development and problem solving. The proposed methodology tailors the assessment phase to the needs of the improvement phase. The LCA times are diminished not by a general lack of detail, but rather by identifying the important areas and simplifying the unimportant ones. LCA results are displayed with a clever infographic, and product criticalities are defined not by each component environmental impact, but by each component improvement potential. Criticalities are then weighted across multiple indicators (including cost and energy consumption) to provide the designer with a ranking of the material and energy flows most likely to be improved. The improvement phase is thus greatly enhanced, and can achieve the full potential of eco-improvement guidelines and problem solving tools; all the while providing the user with a set of visualization and comparison life cycle maps that allow to track the effects of any change in product or process characteristics.

The methodology has been tested on multiple industrial case studies confirming its feasibility. Further development is needed to automate the mapping system, which is as of now mostly done by hand. Furthermore, while each module has been defined and characterized, the procedure still needs to be integrated in a single system.

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