Title:
# Mapping Product Life-cycle Knowledge for Eco-improvement

Authors:
Davide Russo, davide.russo@unibg.it, University of Bergamo
Marco Serafini, marco.serafini@unibg.it, University of Bergamo
Caterina Rizzi, caterina.rizzi@unibg.it, University of Bergamo

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## Introduction:

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. The novelty of the approach lies in its focus toward problem solving rather than environmental certification. 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.

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; 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.
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Main idea:
The proposed life cycle mapping module is part of a comprehensive Eco design suite called i-Tree [3], which was 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 workflow is centered around the mapping module, much like Gabi's interface. All material and energy flows of the product life cycle are entered, with a drag and drop procedure, directly on a diagram called the inventory map. 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 the final product. It is, in essence, the description of the product entire life.

A life cycle analysis is continuously performed, as a background task, while the user builds the inventory map. Thus, the environmental impact of each flow is automatically updated with each change and addition to the inventory map. In fact, the user has the option to shift from the inventory map to the impact map, at any stage during the Life Cycle Inventory. The impact map (

Fig. **1**) is the real heart of the procedure. Once the reference product impacts have been assessed, 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 footprint.

### *Integrated selection of eco-improvement guidelines*

However, i-Tree LCM module sets itself apart from available LCM solutions, as it is not simply a visualization tool. The designer can interact with the map by clicking 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 [3]; they are very specific to the type of flow and the life cycle phase from which the flow was selected. This prevents the use of generic suggestions, and narrows the scope of the proposed action.

### *Visualization of possible eco-improvement trade-off areas*

As no change on the product life cycle has only positive effects, it is imperative to keep track and anticipate the major trade-offs that the designer will encounter. When working with very specific guidelines, it is possible to foresee possible tradeoffs arising from the considered action; be it reducing the product mass or changing one of the materials.

Since there is usually more than one trade-off for each improvement action, we developed a simple graphical way to highlight the life cycle areas most likely to be affected by the proposed product or process change. This graphical representation makes use of the aforementioned impact map and is accessible directly from it, 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. 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. The proposed life cycle mapping methodology features a multi-level approach that allows the designer to effectively build and analyze the inventory of a complex product. As the map levels go deeper, more detailed information is given, while shrinking the scope of the life cycle to a single process or operation (Fig. 3).

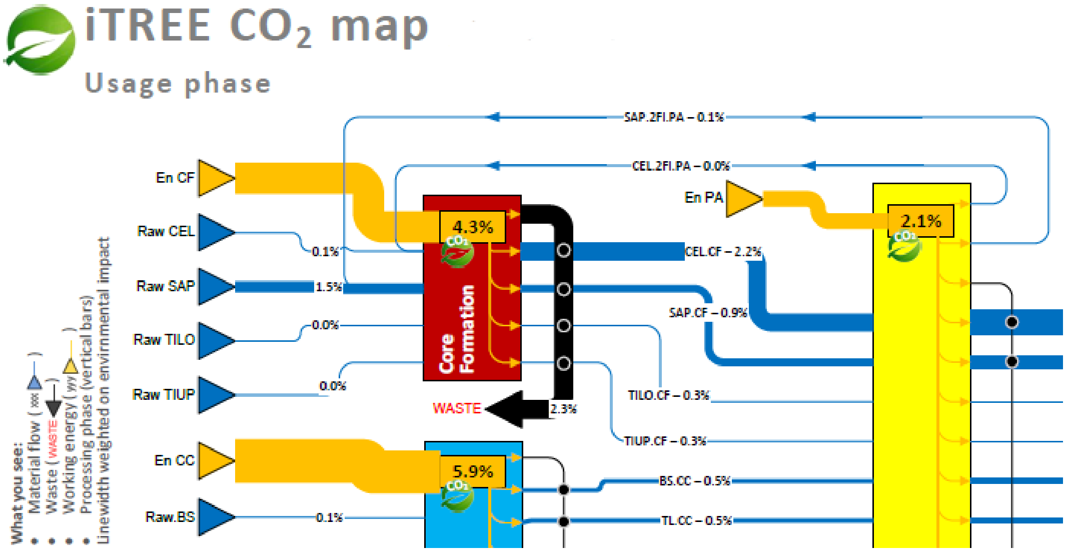

Fig. 1: Environmental impact Map.

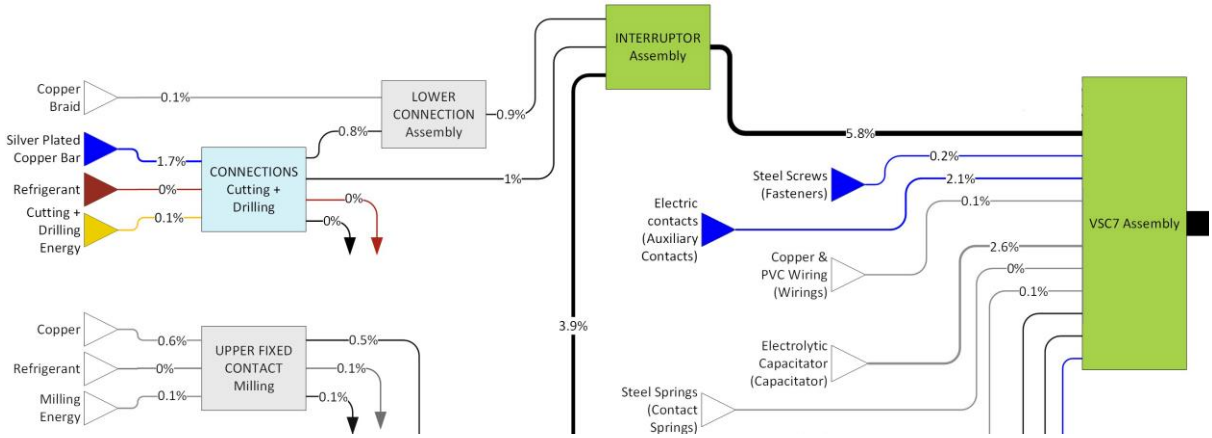

Fig. 2: Visualization of possible eco-improvement trade-off areas.

Three levels have been defined so far. The topmost level gives a broad view of the entire life cycle. Flows and processes represent sub-assemblies that make up the entire product. For instance, a car would be broken down into its core components (Fig. 4): the engine, the frame, the electronics, the transmission, etc. The second level shows the main processes and components of the selected core sub-assembly. For example, the second level map of the engine features a further subdivision of inner parts in sub-assemblies; i.e. the crankcase, the piston assembly, the crankshaft, the valves, etc. At this level, processes are still mainly assemblies, while flows show aggregated material and energy consumption; i.e. the overall aluminum required for the crankcase and the energy consumption of the complete crankcase manufacturing. The third and final level holds the raw data of material and energy consumption for each product component. Primary and secondary manufacturing process make up the nodes of the map, while flows are now single materials and energy consumption. For example, the third level of the crankcase 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 and combined with the results of each sub-assembly, to make up the overall environmental impact.

Clearly, as the map detail rises through the levels, the map also branches into sub-maps for each component and part of the product. 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.

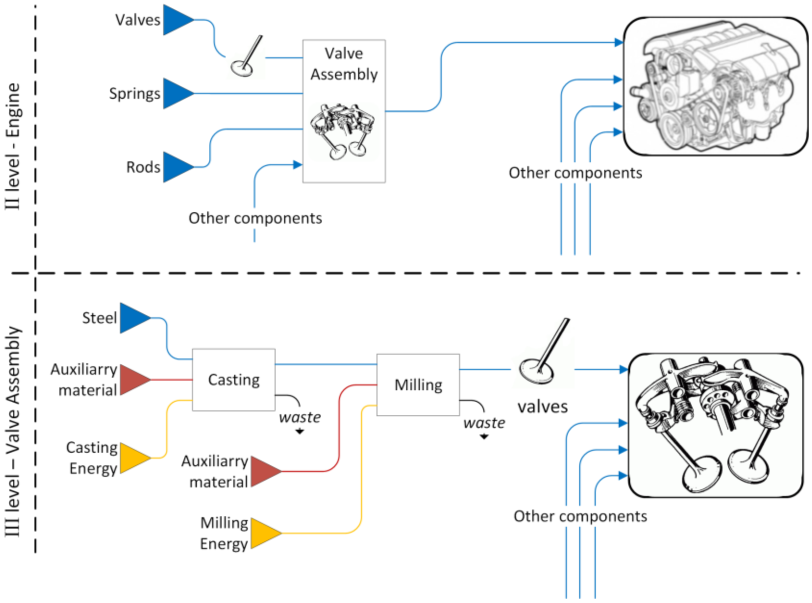

Fig. 3: Multi-level approach to inventory and impact mapping of complex products.

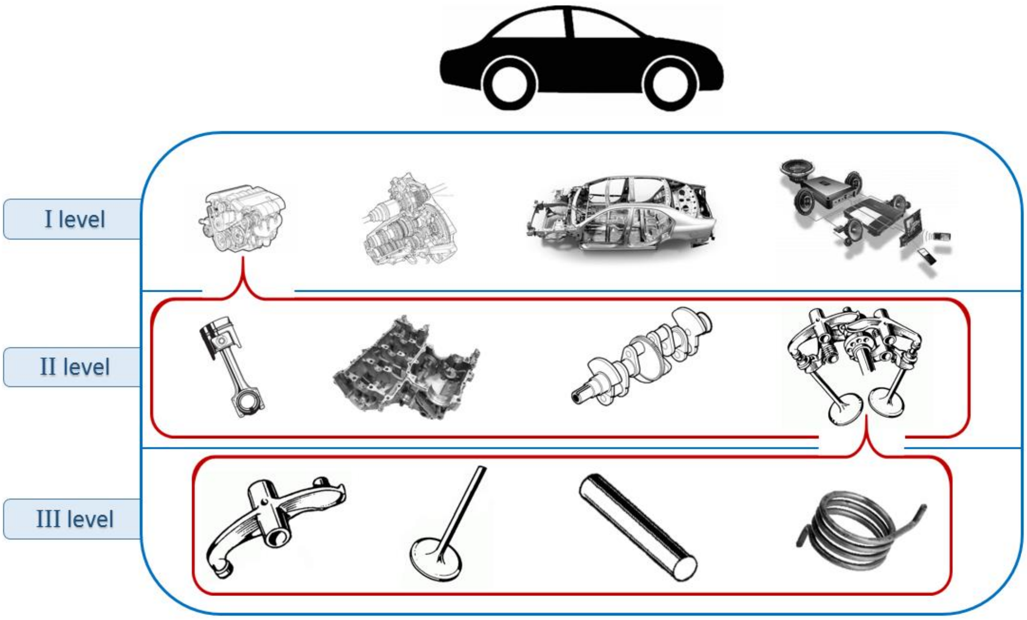

Fig. 4: Example of a multilevel inventory for a complex product.

*Criticalities identification*

Life cycle criticalities are often confused with the relative impact of each flow. Our impact map, just like a Sankey diagram, 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. Trying to redesign this component is probably not cost and time effective, and has a small margin of improvement. On the other hand, a low impacting component may be removed altogether, or improved with little effort.

To show the improvement potential of each material and energy flow, we devised a criticalities identification module, based on TRIZ Ideal Final Result (IFR), and a material and process selection scheme [4]. TRIZ IFR is used to identify the theoretical ideal result of each flow. For example, the ideal result 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. 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 the Granta CES database [5], 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.

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.

## 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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