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Anticipating the identification of contradictions in Eco-design problems

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Abstract

Eco-improvement tools aim at identifying the most critical areas of a product life cycle, thanks to eco-assessment techniques like LCA. The designer is then encouraged to intervene by modifying the product or the manufacturing process characteristics. However, even a slight change of the product life cycle can seriously affect other parts of the cycle itself. Usually, this influences are hard to predict. Only an expert of LCA could effectively anticipate the major repercussions of a life cycle alteration. However, with the introduction of abridged aLCA, life cycle analysis has become a tool for the common designer, which usually doesn't have the expertise to identify the great number of interdependences involved. In these cases, the designer's efforts in reducing product environmental impacts can be ineffective or even counterproductive.

This paper proposes a method and tool, called contradiction prompter, which integrates TRIZ in Life Cycle Assessment. Once environmental criticalities are defined by LCA, a set of guidelines are suggested to intervene on the product. The contradiction prompter collects a set of predefined typical contradictions that can arise when adopting a specific guideline. This can limit the typical trial and error approach and reduce the risk of ineffective redesigns.

The framework has been clarified through an exemplary case study, dealing with the redesign of a moped wheel.

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Keywords: TRIZ, contradicitons, LCA, Ecodesign.

1. Introduction

Product development has changed in recent years to include a wider array of requirements. New products not only need to function well, but also need to look well, have market appeal and be eco-sustainable. These new requirements have expanded the horizon of product development well beyond the factory gates to include

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distribution, use, maintenance, disassembly, and disposal. Design for X that target each of these phases singularly have seen great development. For example, design for disassembly has been applied successfully in the electronics and automobile industry. However, there isn't always a dominant phase which obscures all others. PLM systems allow to oversee every aspect of a product life cycle, by supplying and organizing a common database of knowledge about the product and its manufacturing process. Such systems have become a crucial part of product development and innovation, as shown by their growing diffusion.

Nomenclature

PLM Product life management
TRIZ Theory of inventive problem solving
LCA Life cycle assessment
aLCA Abridged life cycle assessment
LCI Life cycle inventory
LCM Life cycle mapping

With the growing interest in the environmental footprint of a product, designers have to account for manufacturing, use and disposal impacts, from the first stages of development. This new trend has sparked the need for life cycle modeling tools that give the designer an overview of the entire life cycle, while providing environmental impact assessment. At present, there's a plethora of commercial and open source LCA software, all stemming from the ISO norm 14040 on life cycle assessment and life cycle costing. However, the main drawback of the classical LCA approach is the immense amount of information required to compile a through life cycle inventory (LCI) of all material and energy flows that affect the product. Once the LCI is complete, however, the software simply converts each flow into an environmental impact represented by a series of indicators (most commonly, equivalent kilograms of CO2).

In order to cut down on LCA times and make it a viable tool for product development, aLCA (abridged life cycle analysis) was born. This new approach provides a simplified inventory that uses a series of approximations to allow the designer to map a product life cycle in a matter of days. The results are not as accurate as a complete LCA, but they're good enough for the first stages of product development, where the greatest environmental benefits can be achieved. Furthermore, aLCA is accessible to less experienced users, thus encouraging its spread through SMEs that typically don't have the resources for a dedicated LCA department.

The authors have developed a methodology, called Eco- OptiCAD, which combines a series of modules for life cycle assessment applied to product development (Fig. 1). The aim of Eco-OptiCAD is to provide a platform for both eco- assessment and eco-improvement.

In recent years we have developed:

- A life cycle mapping module (LCM), which displays a complete map of the product life cycle (Fig. 2) in terms of quantities, cost, and environmental impact. This is the visual core of Eco-OptiCAD, where the designer can track any change in product life cycle and environmental footprint.
- An aLCA software that automatically converts the life cycle inventory to cost and environmental impact.
- A comprehensive set of eco-guidelines, derived from our extensive eco-design experience and a reformulation of the standard TRIZ principles.
- A material selection scheme based on an extensive material database.
- A set of tool-specific guidelines for the use of topological optimization as an eco-improvement tool.

While aLCA has 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. The complexity of a product life cycle, entails that modifying a single flow usually provokes a series of repercussions. These repercussions are usually a mix of positive and negative effects that change the environmental impact of other flows. Thus the benefit of changing the manufacturing process can only be quantified by re-running the aLCA and may sometimes result in a worsening of the environmental impact.

In order to anticipate and possibly avoid such negative effects, we propose a new addition to our Eco-OptiCAD platform in the form of a contradiction prompter. This module alerts the designer of any possible negative effect, which might result from the proposed eco-improvement action, and defines a physical contradiction based on: EP1 (what the designer is trying to achieve) and EP2 (what most likely will be negatively altered by the pursuit of EP1).

By not only highlighting negative effects, but also posing the problem as a contradiction, the prompter pushes the designer to make use of TRIZ tools in order to find an innovative solution.

2. State of the art

Physical and Technical Contradictions represent the most precise way to formulate an inventive problem. They provide a clear indication of which direction should be taken and which parameters have to be used to model possible solutions. A contradiction exists in a system whenever to improve one of the system parameters, another one deteriorates. For example, if we attempt to make a product lighter by making it thinner, it also gets weaker.

The contradiction is the pillar of ARIZ, the algorithm of inventive problem solving created by Altshuller. The last Altshuller's official version of ARIZ, called Ariz 85-c, starts by defining a technical contradiction and then solves it step by step. From Ariz 85-C to date, many attempts to improve the formalization and definition of contradictions have been proposed [1–3].

In 2012 Russo [3] proposed an algorithm consisting of four phases, supporting the user step by step, from the definition of the initial situation to the formulation of the physical contradiction. Contradiction terms like control parameter CP, and evaluation parameters (EP1 and EP2) are taken from the OTSM theory [2].

This paper addresses all systems where EP1 can be formulated as a green target. For example, the reduction of equivalent CO2, by minimizing mass or transports, increasing the product lifetime or reducing its energy consumption. The next step is to identify an alternative system to the given one, where EP1 is always satisfied, but some other requirements have worsened. This step needs knowledge, but also creativity. Eco-improvement checklists [4], [5], guidelines [6], [7] and analytical tools [8], [9] have been evolving to support this task, but none of them deal with TRIZ contradictions. Literature from the TRIZ community indicates some attempts in the past for the integration of TRIZ with eco improvement methods like eco-checklists [10], Eco compass [11], and design for disassembly [12], [13]. In recent years green design methods inspired by TRIZ are increasing [14–18].

Another research branch aims at customizing classical TRIZ tools [19], [20] as the 40 principles or the contradiction matrix [21] to support Eco-design. Finally, [22], [23] aim at including more theoretical TRIZ fundamentals as the Laws of evolution and the System Operator, into an Eco-design approach.

Overall, the main limit is the lack of a method to suggest a greener alternative to the given system, while taking into account all possible trade-offs. From here the idea of creating a link between a database of Eco-guidelines and a contradiction prompter, that forewarns the designer of any possible contradiction, resulting from the proposed product redesign.

3. Context: Eco-OptiCAD

In the last few years, the University of Bergamo has developed and tested a new eco-assessment and eco-improvement methodology called Eco-OptiCAD (Fig. 1). This new approach to eco-design was conceived from the ground up to be able to assist the designer through each phase of product development.

The workflow starts with a mapping, by use of a modified IDEF0 diagram, of all material and energy flows of the product life cycle. Thanks to this diagram (Fig. 2), called *inventory map*, where material and energy quantities are collected and arranged, a first life cycle analysis of the reference product can be performed. In order to automate the process, we built our own aLCA software, which can be compiled automatically once the inventory has been completed. The aLCA computes an overall impact as well as the relative impact of each inventory flow. It is then possible to visualize each flow relative contribution on a new diagram (Fig. 3) called *impact map*, which highlights the most critical flows as the thickest lines.

The *impact map* 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. 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. Typical suggestions are: the use of CAE software, material and process selection tools, TRIZ principles, and optimization tools. Guidelines are very specific to the type of flow and the life cycle phase, thus preventing the use of generic suggestions and narrowing the scope of the proposed action.

With selective and very specific guidelines, it is possible to foresee the most common repercussions of a change in product or manufacturing process characteristics. As no change on the product life cycle has only positive effects, it is imperative to keep track and anticipate the major dependencies. And, with both positive and negative inter dependent effects, a TRIZ contradiction is the best way to illustrate the problem.

Thus, we integrated a new module called the *contradiction prompter*, which provides the user with a set of possible contradictions arising from the proposed action; be it reducing the product mass or changing one of the materials.

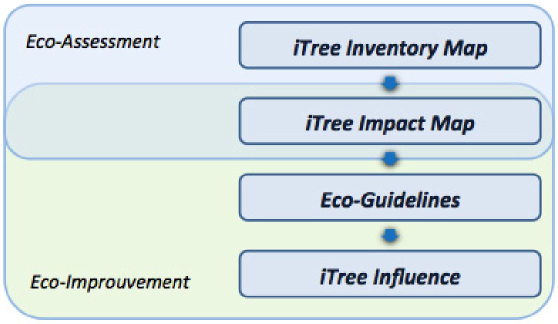

Fig. 1. Eco-OptiCAD methodology steps

Thanks to how Eco-OptiCAD was developed around the TRIZ theory applied to eco-improvement, this evolution was natural and supported by the procedure scheme.

4. Eco Contradiction prompter

While aLCA has 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, the more we act on one of the first phases, like manufacturing and pre-manufacturing. These repercussions are usually a mix of positive and negative influences. For example: changing the manufacturing process for a more energy efficient one may also result in a lighter product, which in turn means less material consumption. However the new process might make use of more auxiliary materials like refrigerating oil. Thus the benefit of changing manufacturing process can only be quantified by re-running the aLCA and may sometimes result in a worsening of the environmental impact.

Improving a product ecological footprint is all about tradeoffs. There is no safe action that guarantees only positive influences throughout the entire life cycle. The benefit of any alteration can only be gauged by weighing all positive effects against the negative ones. This mechanism contributes to a trial and error approach which searches for the best trade-off, rather than trying to highlight and eliminate the negative effects brought about by the life cycle alteration.

Instead of optimizing the product life cycle, we provide the means to anticipate these trade-offs and present them as contradictions. This empowers the designer to use all classical TRIZ tools to solve such contradictions and develop a possibly revolutionary product.

In order to explain how we were able to map the most common contradictions arising from a change in the product life cycle, we must first talk about positive and negative effects. Positive effects are usually easy to anticipate. The main positive effect is the goal of the change in product characteristics.

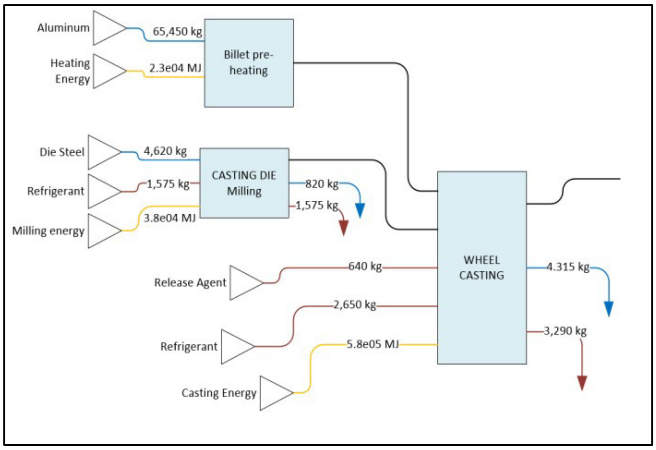

Fig. 2. The Inventory Map maps the entire product life cycle in terms of processes, material flows, and energy flows

Typically: less energy or material consumption, a lower level of toxicity, a simpler distribution network, and so on. Secondary positive effects are consequences of the actions taken in order to achieve the main positive effect. From a psychological point of view, secondary positive effects are still relatively easy to anticipate, because they reinforce the designer's suggested course of action. For the same reason, negative effects tend to be neglected and are harder to anticipate. They too are consequences of the actions taken in order to achieve the main positive effect, but, since they are not sought to begin with, can become apparent only when rerunning the aLCA. As of today, only an expert of LCA could effectively anticipate the major repercussions of a life cycle alteration. However, with the introduction of aLCA, life cycle analysis has become a tool for the common designer, which usually doesn't have the expertise to identify the great number of interdependences involved.

For this new kind of LCA users, there's a need for a tool that can highlight the main areas influenced by the proposed life cycle alteration. To create such a tool, we must first map and organize all possible contradictions, in such a way that they can be selected at the relevant time.

Thanks to our Eco-OptiCAD methodology, this can be achieved quite easily as follows.

Defining EP1

Our LCM module provides a map with all material and energy flows and corresponding environmental impact (Fig. 3). From this map, the designer will choose a flow to improve, which in turn defines the first evaluation parameter (EP1). If the designer were to choose a transport flow, the system would automatically recognize *transport energy* as the contradiction EP1. Most common EP1 are material and energy consumption, in the form of: raw materials, auxiliary materials, process energy, use energy, etc. They represent what the designer wishes to directly improve.

Choosing CP

As aforementioned, once the designer selects a critical flow, one or more guidelines will pop up (Fig. 4) suggesting a course of action. The means in which the flow EP1 will be improved is the contradiction control parameter (CP). Each guideline targets a specific CP through which to improve

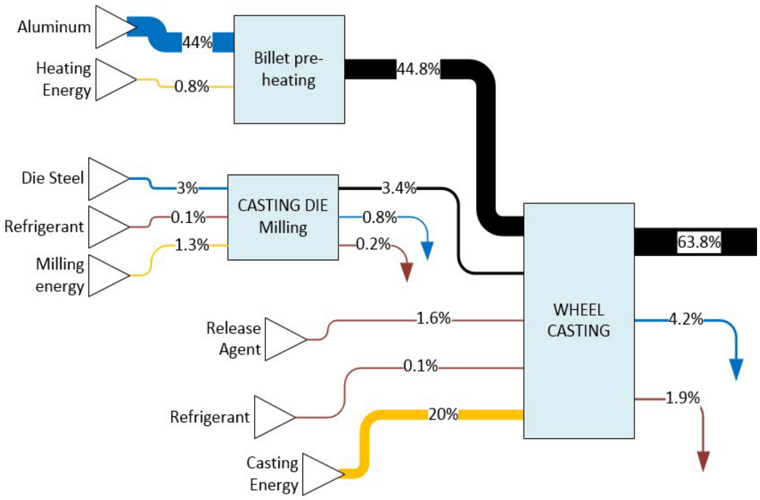

Fig. 3. The Impact Map traces the environmental impact growth in terms of equivalent CO_2 production throughout the product life cycle

the selected flow. Overall, 17 CP have been found, like: mass reduction, waste and losses reduction and process or material change. Our guidelines have been arranged by control parameter in the iTree-Matrix, thus can provide automatic feedback for the contradiction creation.

Defining EP2

The chosen guideline will suggest a tool or a method to act on the CP. By knowing how the tool works or what the actions of the proposed methodology are, we can trace in advance most of the effects along the life cycle and provide the designer with all relevant second evaluation parameters (EP2). By mapping and organizing all major EP2, we can bridge the designer lack of LCA experience, by providing a set of possible contradictions for each action taken on the product life cycle.

For example, if the designer were to choose a material flow in the pre-manufacturing phase, the EP1 would be raw material consumption. To improve such a flow, guidelines will target mass reduction, waste and losses reduction and number of components reduction; each of which would be the contradiction CP. If the designer were to choose mass reduction, the relevant guideline would suggest using an optimizer to change the product geometry to a lighter one. By knowing how an optimizer works, we can suggest a set of possible EP2. In this case, an optimizer tends to raise the complexity of the product shape, thus possible EP2 are: process energy, life expectancy, auxiliary materials consumption. A possible contradiction is shown in Fig. 7.

To automate the process of anticipating all possible contradictions, we gathered all EP2 in a new Eco-OptiCAD module called *iTree-Influence*. This new matrix maps the main areas of influence of each eco-improvement tool. Areas are divided by macro category (energy, transport, material, packaging, recycling and process-auxiliary material) each subdivided by life cycle phase (pre- manufacturing, manufacturing, use and end of life). By following the steps of the Eco-OptiCAD methodology, we can easily trace each designer's choice in terms of EP1, CP and tool, while finally providing a set of possible EP2 through the *iTree-Influence* matrix.

Once the designer has chosen a guideline, he will be prompted to assess one or more negative effects, in the form of EP2, which may arise from the use of the chosen guideline.

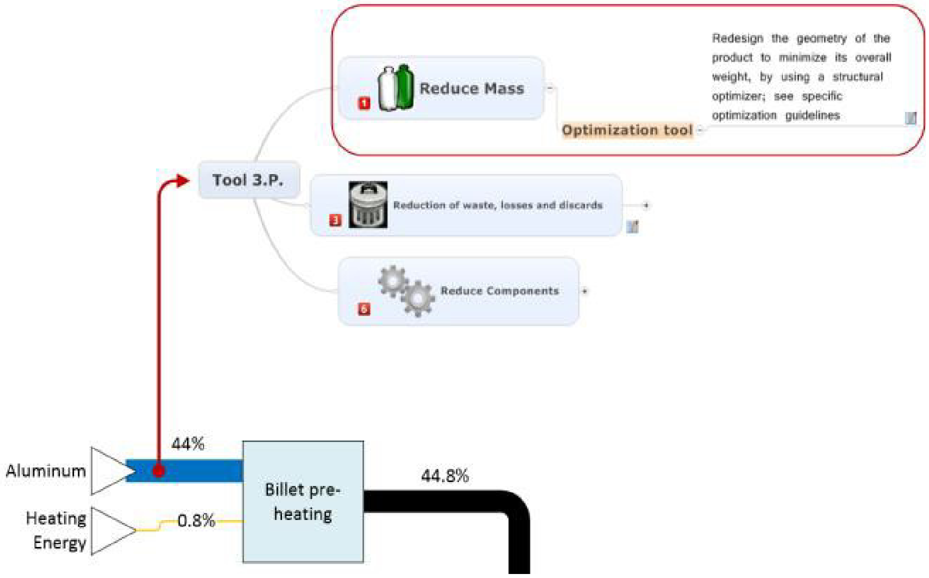

Fig. 4. Eco-Guidelines are shown as interactive popups directly from the Impact Map

Based on his experience with the product under development, the user may discard non relevant effects and focus on the most pertinent one, or he may wish to keep track of all EP2. 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 EP2 makes use of the aforementioned impact map and is accessible directly from it, after choosing a flow to modify and a relative guideline.

Once a consistent negative effect has been chosen, the user will be presented with a physical contradiction, created on the previous choices of life cycle flow and improvement guideline.

5. Exemplary case study

To better explain the importance of the contradiction prompter, we will outline a simple yet comprehensive case study of a moped wheel eco-improvement. The case study will follow the steps portrayed in (Fig. 1).

5.1. Eco-assessment

When redesigning an existing product, the first step is to assess and map the current version footprint. Thus we proceed to create both inventory (Fig. 2) and impact map (Fig. 3) for the current version of the product, the latter of which shows a criticality on the primary material consumption; 44% of the overall environmental impact. When using the impact map it's easy to keep track of the environmental impact growth throughout the product life cycle and pinpoint not only the most critical flows, but the effect of every change in the product characteristics.

5.2. Eco-improvement

One of the most effective ways to improve a product environmental footprint is by using less resources. Developing a lighter product typically has benefits in both raw material consumption, use energy and distribution energy. Eco-OptiCAD allows the user to work around the impact map, by simply selecting the material or energy flow he wishes to improve upon. Based on the type of flow and the life cycle phase, a popup will appear with all relevant eco-guidelines (Fig. 4). The first proposed guideline suggests: "*Redesign the geometry of the product to minimize its overall weight, by using a structural optimizer.*"

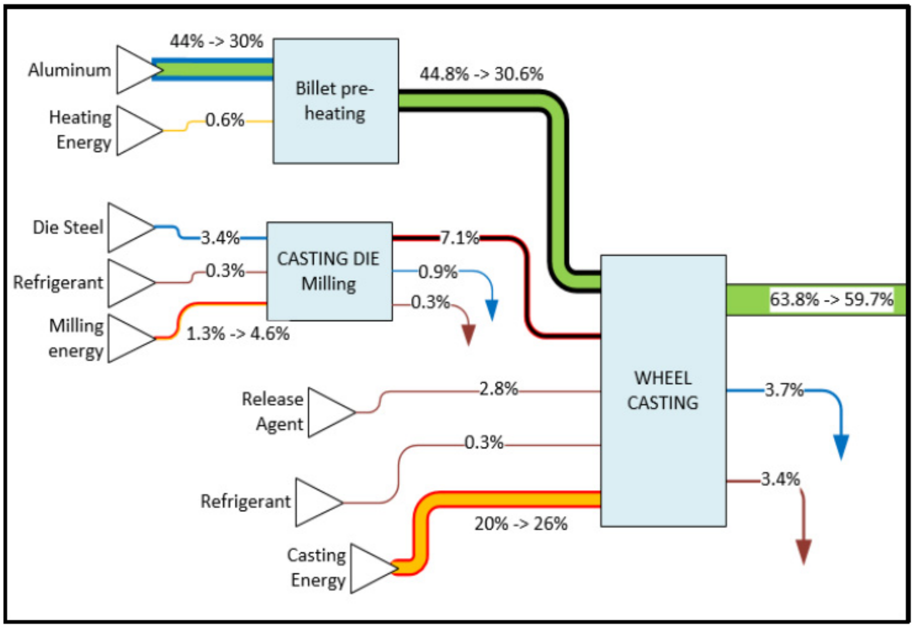

Fig. 5. The Impact Map can show an overlay of the new design performance over the reference product

However, such a task is not without drawbacks: a reduction in mass usually results in a more complex and possibly more fragile shape. Typical EP2 are: process energy, auxiliary material consumption, product life expectancy, and packaging materials. In [24] a moped rim was redesigned (Fig. 6). A lighter wheel meant lower resources consumption, but a more complex geometry made for a more energy demanding manufacturing phase. The resulting contradiction is shown in (Fig. 7).

The results of a structural optimization can be seen in (Fig. 5). The new geometry has achieved a 30% reduction on Aluminum consumption (highlighted in green) at the cost of a general increase in the manufacturing energy and auxiliary materials consumption. Consequently, without warnings from the contradiction prompter the overall impact has been reduced by only a few percentage points.

5.3. Contradiction Prompter

For the case study at hand, the contradiction prompter would suggest that a mass reduction, aimed at minimizing resources consumption by using a structural optimizer, could result in: *increased process energy, increased process auxiliaries consumption, decreased product life expectancy,* and *increased maintenance*. All of these are presented as contradictions, as in (Fig. 7). The user will have a sense of what are the possible outcomes of the selected eco- improvement course and can make use of all common TRIZ tools to solve one or more of the proposed contradictions.

For example, the choice between all the different topologies created by the structural optimizer (Fig. 6) was guided by the contradiction prompter, which forewarned of a possible increase in process energy. This produced an unexpected result: by taking into account the complexity of the resulting shape, the most ecological design was the old wire-spoked wheel. The complex yet light shape, is achieved by manufacturing each component separately and then assembling the wheel. The complex geometry is broken down into easy to manufacture components, thus limiting the energy consumption of the manufacturing phase. The resulting wheel is both light and easy to manufacture, granting an overall equivalent CO_2 reduction of more than 10%.

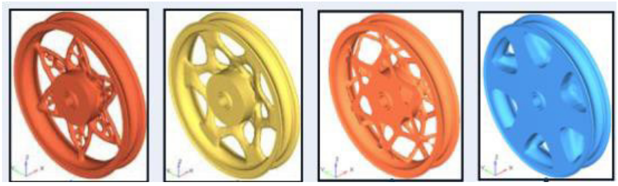

Fig. 6. Moped wheel topological optimization

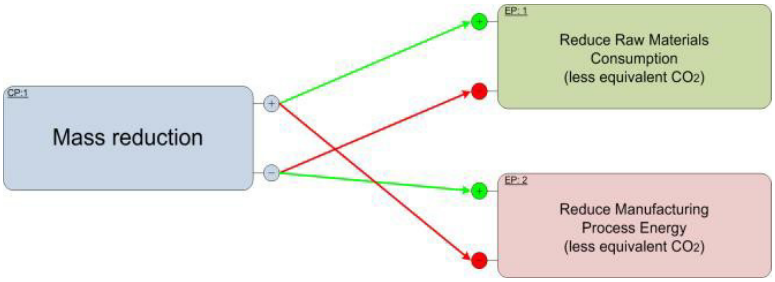

Fig. 7. A reduction in mass is often accomplished with an increase in shape complexity, resulting in a higher processing energy consumption

Contradictions aren't limited to tradeoffs between life cycle flows, but can arise as tradeoffs between different environmental indicators.

For example, changing one of the product materials can affect in diverging ways different environmental indicators. In this case, the *contradiction prompter* can suggest what indicators are most likely to be influenced. In [24] the moped wheel was redesigned by changing the primary material with a high performance one. The resulting geometry was significantly lighter and the production of CO_2 was cut down by 6%. However, high performance materials frequently have toxic compounds which, while not contributing to CO_2 production, can have ill effects on water and soil pollution. As a result, acidification and eutrophication were increased by 4%.

Guided by the *contradiction prompter*, it was possible to redesign the moped wheel by selectively using high performance materials only on critical parts of the wheel, thus limiting the effects on water and soil pollution, while retaining the structural benefits of the new material.

6. Conclusions

The contradiction prompter is not just a way to highlight and track negative effects caused by the designer's intervention, but it's foremost a new way of thinking eco- improvement. By rewriting each guideline as a contradiction, the designer is pushed to make use of TRIZ tools to innovate the product, rather than optimize a starting configuration. Making a lighter product that suffers from a reduction in life span has always been a matter of optimizing the two sides of the problem; thus making a product as light and long lasting as possible. Thanks to the contradiction prompter, by not only highlighting the fact that a lighter product may suffer from a shorter life span, but also posing the problem as a contradiction, the designer is pushed to solve it; thus finding a way to make the product lighter without hampering its life expectancy.

The feasibility of the contradiction prompter has been tested on numerous case studies and has been found to match our previous findings, in terms of contradictions anticipation. However, since the EP2 *iTree-Influence* matrix is built upon our own experience in eco-improvement tools, it is an ever-developing database which must constantly be kept up to date, and could benefit from a collaborative development. It should also be noted that it is harder to track all possible EP2 the less specific is the field of action of the proposed tool.

Finally, the software implementation is still under development, but the goal is to center every step of the procedure around the impact map. The user should be able to access every flow information, guideline, and contradiction directly from the map, which in turn provides constant feedback on every product or process change.

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