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TECHNICO-ENVIRONMENTAL ANALYSIS OF BIOPLASTICS IN A CIRCULAR ECONOMY – VISUALISATION TOOLS FOR SUSTAINABLE MATERIAL SELECTION

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Abstract:

The present study explores the topic of sustainable material choice in early design processes. A visual-based tool is proposed to help designers explore and understand the environmental impact and possible usages of different plastic alternatives, including bio-plastics. Preferences and feedback from designers and material engineers in the field have been collected and used when designing the visual tool. The application and relevance of this newly developed visualization-based tool are illustrated through a case study.

Keywords: Bio-based plastics, environmental impact assessment, carbon footprint, materials substitution, sustainable alternatives, sustainable design, circular economy.

Glossary:

- CE: Circular economy
- GWP: Global warming potential
- LCA: Life cycle assessment
- PA: Polyamide (Nylon)
- PBS: Polybutylene succinate
- PC: Polycarbonate
- PE: Polyethylene
- PET: Polyethylene terephthalate
- PHA: Polyhydroxyalkanoate
- PHB: Polyhydroxybutyrate
- PLA: Polylactide acid
- PP: Polypropylene
- PPS: Polyphenylene sulfide
- PS: Polystyrene
- PTT: Polytrimethylene terephthalate
- PUR: Polyurethane
- PVC: Polyvinylchloride
- S-materials: Sustainable materials
- TPS: Thermoplastic starch

1. INTRODUCTION

1.1. CONTEXT AND MOTIVATIONS

It is estimated that around eight million tons of poorly-used plastics enter the oceans every year. The degradation of plastic is very difficult, and during this process, there could be significant emissions of carbon dioxide and many other toxic compounds, e.g., around three kilograms of CO₂ is emitted per kilogram of plastic burned on average (Thakur et al., 2018). On this basis, new advanced and sustainable materials, like bioplastics, are being developed not only to face pressing issues like petroleum-based plastic pollution but also to improve mechanical properties and profitability. There are indeed several ways to make plastic more sustainable – from using more renewable content and reclaiming and recycling material, to reducing energy needed for manufacturing and returning material to nature at the end of its life (GreenDot, 2016). Replacing petroleum-based plastics with renewable, reclaimed, or recycled materials can be a convenient way to lighten the environmental footprint of products. In fact, biocomposites made from industrial by-products like reclaimed wood fibers and recycled plastic can encourage manufacturers to reduce landfill waste.

Though, their actual adoption in new product development needs to be augmented. As the design phase has a key influence on the sustainable performance of products over their lifecycle, providing designers with appropriate and practical tools for green material selection is of the utmost importance. On the one hand, materials selection is indeed one of the main phases of the product design process and can have a significant impact on the overall lifecycle of products. On the other hand, we believe that integrated visualization-based tools can effectively support designers and material engineers in the screening and selection of sustainable alternatives during the early design stage. Yet, the current lack of robust and precise visualization frameworks represents a barrier in advancing the efficacy of sustainability analyses (Bianchini et al., 2019; Raoufi et al., 2019). In addition, regarding the environmental impacts of bio-based plastics, to the best of our investigations, there is currently no satisfactory database sufficiently complete and up-to-date.

1.2. RESEARCH QUESTION AND OBJECTIVES

In this context, the questions we set out to answer are, therefore:

- What are the environmental benefits of potentially suitable bio-based plastic alternatives in comparison to conventional ones?
- How to facilitate and ensure the selection of greener materials by design engineers during the (re)design and development process of products?

Through the development of a new visualization tool, this study aims to bridge the gap of existing tools and associated databases that unsatisfactorily address the comparison between bio-based plastics and their petroleum-based counterparts.

The objectives are the following:

- To provide a practical, straightforward, and user-friendly visual tool;
- To make informed-decision in sustainable materials selection;
- To educate designers and material engineers on sustainable materials alternatives.

2. LITERATURE SURVEY

To fill these gaps and come up with new solutions, the following approach and resources have been used: (i) a review of state-of-the-art articles on bio-based plastics to extract information about their performance; (ii) a critical analysis of existing visualization-based tools to get inspiration, and to know what features are valued or useful for engineers; and (iii) iterative interactions, through surveys and focus groups, with designers and material engineers, as detailed in Figure 1.

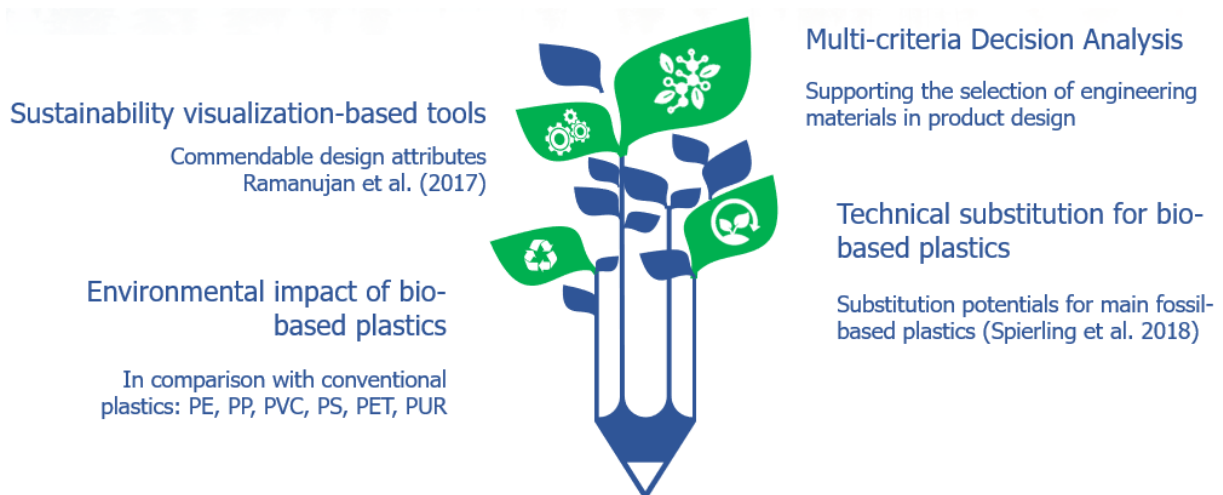


Figure 1 – Inspiration sources

For instance, while Ramanujan et al. (2017) developed a checklist of commendable design attributes of sustainability visualization-based tools, Spierling et al. (2018) provided the substitution potential of the main fossil-based plastics, namely: PE, PP, PVC, PS, PET, and PUR. The technical substitution potential describes which fossil-based plastics can be substituted by bio-based plastics due to similar properties (Spierling et al., 2018). Examples of bio-based and biodegradable plastics include PLA and PHA (Van den Oever et al., 2017). Note that Bio-PE is a bio-based but non-biodegradable plastic.

3. MATERIALS AND METHODS

In addition, to further understand the current material selection process of the industrialists supporting this study (Saidani et al., 2020a), discussions have been carried out about the workflow of how materials are selected for a given part. We actually worked with designers and material engineers to collect their preferences and feedback when it comes to visual tools for material selection.

Most common visualization-based tools that could be used to inform engineers of the environmental impact of different materials have been put together in a survey: Ashby diagram, Scatter plot, Bar chart, Radar chart, Arrow, as illustrated in Figure 2.

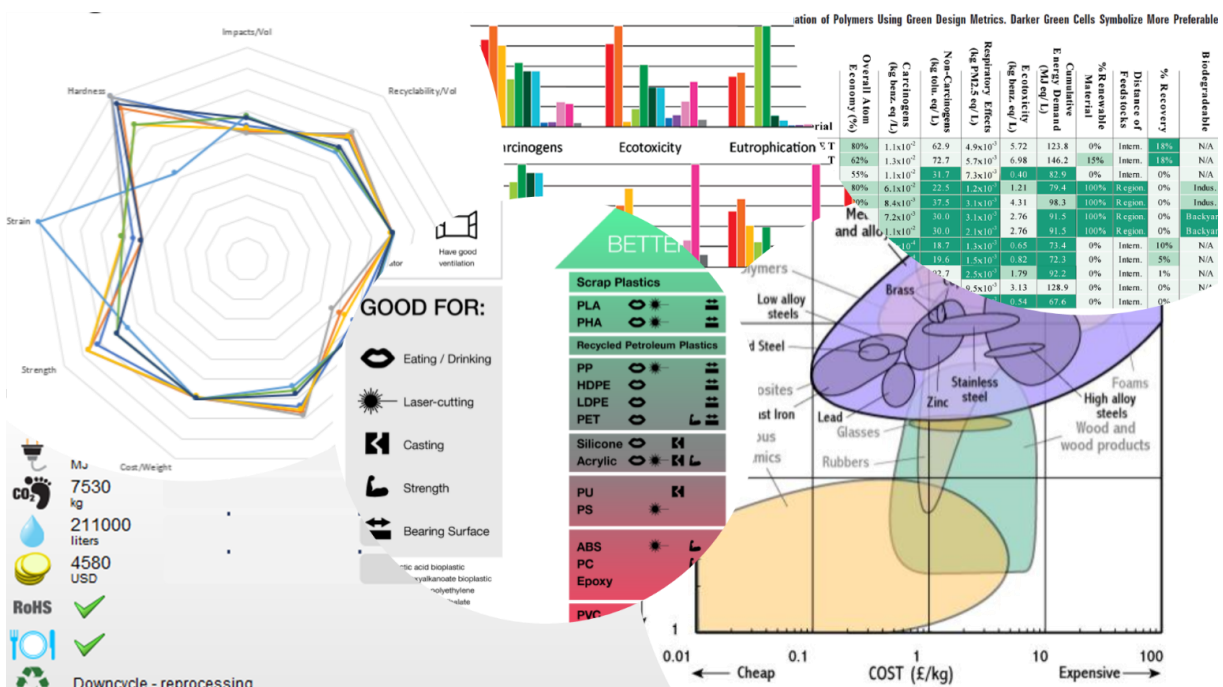


Figure 2 – Overview of visualization-based options

The following questions were asked: (i) Is this tool relevant or valuable for material selection? (iii) How would you assess the design and user-friendliness of this tool, and what could be improved (in terms of design or information displayed)? (iv) Which combination of the tools presented before would you find helpful? (v) Would you find added value to a web-based app of such visual tools, e.g., to select which information to display by just clicking on well-designed boxes?

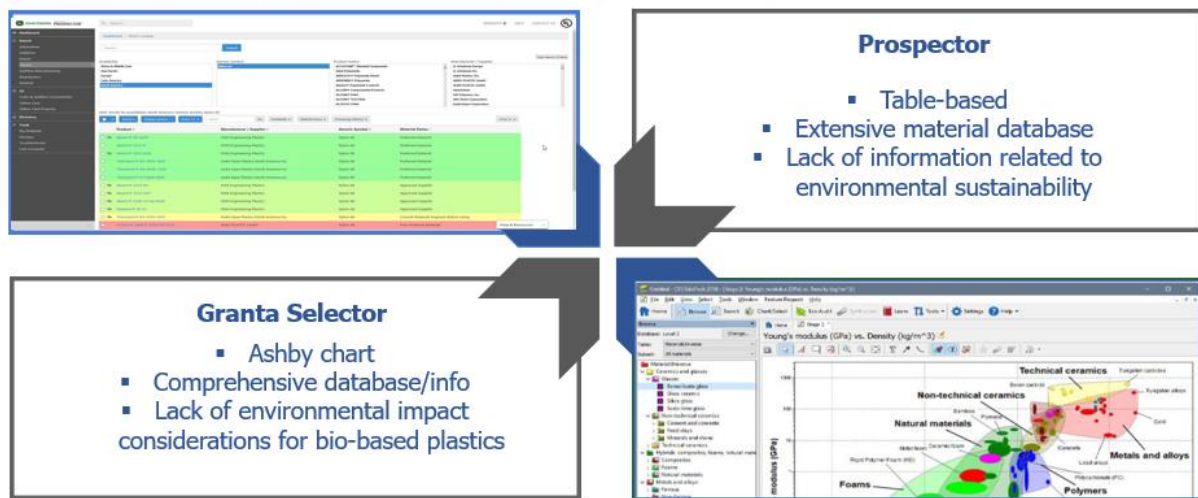


Figure 3 – Commonly used software for material selection

As illustrated in Figure 3, The Prospector is the tool used to search for potentially suitable material, “to narrow down the search before testing based on required material properties”. This tool is convenient to access material datasheets, to compare typical values, as well as to find alternatives and supplier information. Still, it does not include the environmental performance of materials, and the bio-based material options are currently very limited. Similar gaps have been found in other state-of-the-art software such as Granta Selector or current LCA databases. Out of these surveys and focus groups, we got insights on what design and material engineers value most. For instance, with the green arrow, designers could rapidly identify that PLA might be a suitable greener substitute to PP, e.g., in terms of material features, both have “laser-cutting”, and “bearing surface” compatibility.

4. RESULTS AND INTERPRETATIONS

In all, diverse visualization graphs and charts to help materials choice considering trade-offs (e.g., between cost, environmental performance, and desired material properties). To come up with new prototypes, we combined the previous investigations and follow-up discussions with two seniors designers and material engineers. As no single technique meets all the requirements, hybrid visualization tools seemed to be an attractive solution to combine the advantages of individual visualization tools. We merged the valued features of preferred tools (e.g., contrasted colors, logos, multi-dimensional visualization on a single view) to design augmented, practical, and more integrated visualization tools, as illustrated in Figure 4.

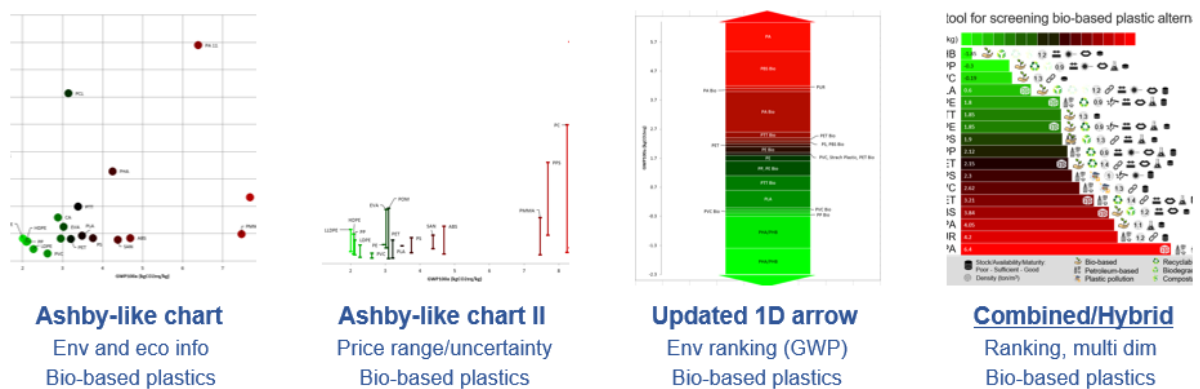


Figure 4 – Prototyping of sustainable material selection and visualization tools

The selected hybrid visualization tool combines the valued features of several separate visualization tools (e.g., quantitative bar chart, contrasting colors, multi-dimensional representation, logos) in an integrated way, as showcased in Figure 5 (Saidani et al., 2020b). This graphical visual interface representing multi-dimensional information can be viewed as an infographic that can either (i) be printed and posted on design and material engineers desktop to inform them on bio-based plastic alternatives, or (ii) be displayed on a computer screen. It allows quickly identifying potential greener/sustainable alternatives during the first steps of the (re)design process.

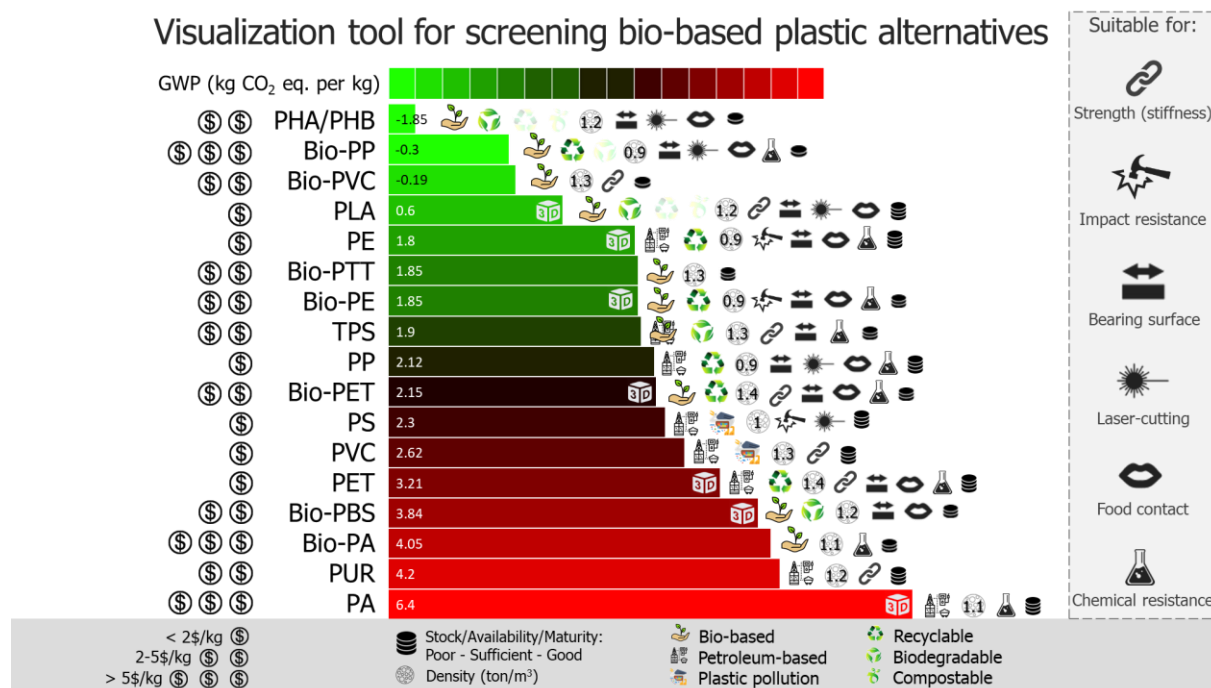


Figure 5 – Hybrid visualization tool for sustainable material alternative selection

All the global warming potential (GWP) values are cradle-to-gate, i.e., including the processing and manufacturing impact of 1 kg of plastic ready to be used. Additional key material information has also been embedded, such as density, price, recyclability, market availability, and other mechanical characteristics. A colorblind-friendly version (with a blue and orange palette, as displayed) is also available on demand. Note that we have also developed a spreadsheet including a macro to automate the ranking of bio-based plastic alternatives, e.g., according to their carbon footprint, to facilitate the update of the tool (with new values or new materials).

According to the first feedback with had with designers and material engineers that collaborated with us, such a visual tool is relevant to communicate easy-to-digest and easy-to-understand information for designers that might not be specifically trained for sustainable material selection or familiar with other tools like life cycle assessment software.

Eventually, to illustrate how the new visualization tool can be simply used to find out possible bio-based material substitutes to reduce the environmental footprint of products, a case study is performed on two real-world products that are currently containing a non-negligible variety and quantity of conventional petroleum-based plastics, as given in Table 1. For product one, results show that replacing all petroleum-based plastics with suitable green plastic alternatives – supporting by the proposed visual tool – could reduce the overall manufacturing impact of this product by 10% in terms of carbon dioxide emissions. For product two, using new bio-based plastics instead of petroleum-based ones could avoid the emissions of more than half a ton of carbon dioxide per product. In this illustrative example, it has been assumed that 1 kg of conventional plastic X could be replaced by 1 kg of drop-in bio-based plastic X.

Original plastic materials (petroleum-based)	Mass (kg)		Sustainable alternatives (bio-based or recycled plastics)	Estimated GWP impact savings (kg CO ₂ eq.)	
	Product 1 Autonomous Lawn Mower	Product 2 Tractor Sprayer		Product 1 Autonomous Lawn Mower	Product 2 Tractor Sprayer
PE	5	480	Bio-PE	- 0.25	- 24
PP	5	60	Bio-PP	12.1	145.2
PVC	0.1	10	Bio-PVC	0.28	28.1
PA	0.1	200	Bio-PA	0.23	470
PUR	2	5	Recycled PUR	4	10
Total	12.2	755	Significance	Manufacturing impact reduced by 10%	More than half a metric ton of CO ₂ avoided

Figure 5 – Case study results (Saidani et al., 2020a)

5. CONCLUSION AND PERSPECTIVES

To conclude, as mentioned by a designer and a senior material engineer, an interesting and valuable perspective would be to create a dynamic dashboard, with light or customizable user interface, containing two or more visualization-based tools to provide further information and even prompt action or decision, as illustrated in Figure 6. Such a dashboard could include complementary information such as circularity indicators (Spierling et al., 2019; Saidani et al., 2019; D'Adamo et al., 2020). A promising and timely perspective for future work is to also develop and deployed appropriate visualization tools to increase customer awareness on available bio-plastic alternatives when purchasing products (Dilkes-Hoffman et al., 2019).

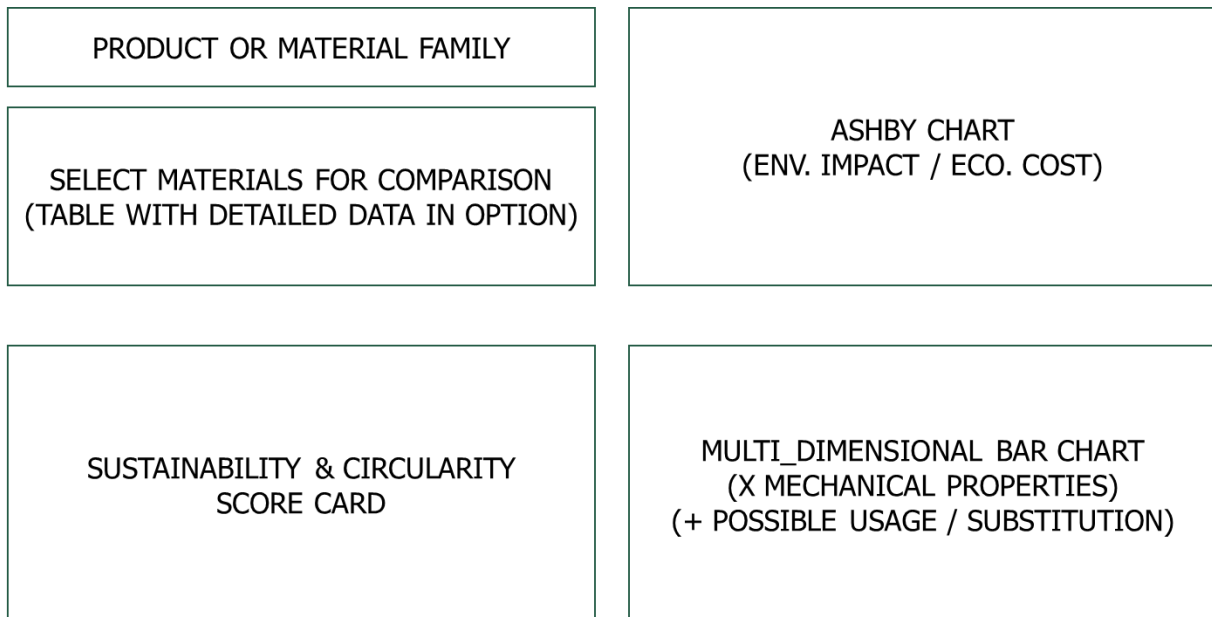


Figure 6 – Mock-up of a dynamic dashboard

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