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Early-stage sustainability assessment to assist with material selection: a case study for biobased printer panels

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ABSTRACT

This paper aims to incorporate sustainability assessment into the material selection processes during early-stage product (re)design, when time and data availability for such assessments are usually limited. A *material selection framework* is presented and illustrated step-by-step with a case study aiming to identify biobased alternatives for petrochemical plastics used for (flame retardant) panels. After an initial screening step, the technical performance of selected materials is measured. A cradle-to-grave screening life cycle assessment compares the environmental performance of the candidate and reference materials on greenhouse gas emissions, non-renewable energy use and agricultural land use per kilogram. A simplified cost analysis is performed. The environmental and economic indicators are corrected for each candidate's technical performance by estimating expected weight changes in the final product based on *material indices*. In this case study, two biobased plastics are found to offer equal or improved environmental/economic performance compared to reference materials. Furthermore, the case study shows that additive production can significantly contribute to the plastics' environmental impacts, e.g. accounting for 5–40% of their cradle-to-grave greenhouse gas emissions. The case study demonstrated that the proposed materials selection framework is a useful tool for early-stage product design.

1. Introduction

Plastics derived from biological resources can potentially limit greenhouse gas (GHG) emissions and the use of finite fossil fuels (Weiss et al., 2012; Hottle et al., 2013). Increasing the biobased carbon content of products has also become a target for many companies (Agro and Chemie, 2015). Meanwhile, compounding has increased the range of available biobased plastic grades, potentially opening up new application areas. Product design processes thus require good material selection procedures to identify suitable biobased plastics and ensure fair comparisons with petrochemical counterparts. Conventionally, only technical and economic aspects are considered from the onset of product development. However, environmental aspects should also be included, because choices made during the early development stages have a large influence on the final product's environmental impacts (Hauschild et al., 2005; Sheldrick and Rahimifard, 2013).

Incorporating environmental considerations into product design is often referred to as ‘eco-design’. Many eco-design tools have been developed, as reviewed for instance by Byggeth and Hochschorner (2006), Hernandez Pardo et al. (2011), and Bovea and Pérez-Belis (2012). These publications illustrate the tools' wide range in terms of eco-design strategy (e.g. material selection, reduction of product use-phase impacts, maximising product lifetimes, or other optimisations), complexity (e.g. data and expertise requirements), and type (e.g. informing, analysis and/or guidance).

Material selection eco-design tools can be highly sophisticated, for instance by combining computer-aided design (CAD) with environmental impact information. Russo and Rizzi (2014) provide an overview of these tools, which are generally complex and time-consuming to use. In contrast, less resource-demanding eco-design tools that can be used to select and/or compare different material options include for instance qualitative or semi-quantitative guidelines (e.g. “avoid toxic materials”), checklists (e.g. Volvo's

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black, grey and white lists), and analytical tools (e.g. multi-criteria analyses, ERPA matrix, LiDS wheel) (see e.g. Byggeth and Hochschorner, 2006; Bovea and Pérez-Belis, 2012).

In addition, Ashby (1999) introduced material property charts in which best-performing candidates are identified by comparing two selected properties of materials. These can be mechanical properties, for example, or environmental indicators (e.g. embodied energy). While less complex than CAD, these tools risk being oversimplified by using qualitative and/or single environmental indicators that do not benefit fully from life cycle assessment (LCA) studies.

LCA is a tool to assess the environmental impacts of a product or service based on a defined functional unit (ISO, 2006a). However, accounting for differences in technical properties between materials can be difficult when defining functional units and reference flows (Cooper, 2003). This is particularly the case for novel materials (e.g. biobased plastics), for which only limited information on material properties may be available, and future applications may still be unknown. Many LCA studies for biobased plastics thus only report comparisons on a kilogram (kg) basis (Shen and Patel, 2008; Chen and Patel, 2012; Hottle et al., 2013). However, per kg analyses fail to reflect differences in functionality and could thus be misleading when used for product design.

Ashby (1999) introduced so-called *material indices*, which can be used to estimate the minimal mass required for a product expressed as a function of material properties (e.g. tensile strength and density). Several LCA studies have used this concept to determine substitution factors (e.g. Cooper, 2003; Lloyd and Lave, 2003), for instance to carry out early-stage environmental assessments of novel materials (Roes et al., 2007). This procedure can thus be used to account for expected weight changes when implementing novel materials, particularly when few material properties are known.

Inspired by this approach, the present paper introduces a material selection framework to be used in early-stage product design (Fig. 1), with the objective of identifying the most sustainable candidate materials without extensive time, resource, or specialised software requirements. Materials are evaluated based on technical performance, environmental impacts and economic aspects. Instead of per kg comparisons, material indices which account for the main product function. Top candidates identified in the framework can be studied further in the detailed design and prototyping stages. The framework targets incremental product redesign, in which a reference material is available and product geometry will not radically change. It initially focuses on biobased plastics, although it can be used to identify more sustainable materials in general.

In this article, the framework is first described in detail (Section 2). Then, a case study is demonstrated for biobased electronics housing panels (Section 3). Section 4 discusses the case study and evaluates the framework and finally the study is concluded in Section 5.

2. Methodology: material selection framework

Fig. 2 shows a generic overview of material selection processes (left) and a schematic overview of the proposed framework (right). During the selection process, increasing constraints are used to narrow down a selection of materials and identify the best choice(s). After screening and testing steps to identify candidate materials (steps 1–3), the expected weight changes in the end-product (i.e. *material substitution factors*; MSFs) are estimated based on material indices (MIs) in step 4 (Ashby, 1999). The candidate materials' environmental and economic performance is then assessed, the results are corrected using MSFs (step 5) and finally the materials are ranked (step 6).

Step 1: Defining goals and constraints

In the framework's first step, the *objectives* (Ashby, 1999) of the assignment are set and a reference material is selected. The objectives determine which indicators are used to rank alternative materials (Step 5). Since this framework aims to identify sustainable materials, typical objectives will be to minimize the environmental impacts and costs associated with the function fulfilled by the product.[1] For example, companies can aim to reduce GHG emissions associated with their products or aim to become certified with a specific eco-label. The reference material (typically the currently used material) is a starting point when screening for alternative materials (Step 2).

Secondly, the product's *function*, *constraints* and *free variables* (Ashby, 1999) should be understood. Its function determines which material indices are relevant and should be used to derive material substitution factors (Step 3). Constraints set the design requirements and limitations, and are used when screening materials (Step 2). They can be subdivided into *geometric constraints* (e.g. fixed product dimensions), *functional constraints* (e.g. specific loads that must be supported) and *material constraints*[2] (i.e. related to intrinsic material properties or other attributes not determined by product geometry). Free variables are the product parameters that can be changed (e.g. a wall thickness).

Step 2: Screening

Screening entails making a rough selection of potential alternatives to the reference material. First, *screening criteria* are defined, which are subsequently used to filter out unsuitable materials based on their material properties.

Three types of screening criteria can be distinguished. *Discrete* criteria refer to properties that a material either has or does not have. *Threshold* criteria are used for continuous properties where all values exceeding the threshold are considered sufficient. Finally, *interval* criteria can be used for continuous properties if only values within a particular range are acceptable.

The constraints defined in Step 1 can be translated into screening criteria. The properties of the reference material can be used as a starting point to determine the values used for threshold criteria and interval criteria.[3] To translate functional constraints into criteria, the material properties that determine performance in this function should be used for screening. For example, if a product should resist a certain top load, a material's stiffness determines its performance and should thus be included as a screening criterion. All screening criteria should be measurable, e.g. by referring to specific testing standards.

Materials which meet all screening criteria are then selected from the pool of available materials. Material databases (e.g. MDC, 2015; UL, 2015), suppliers and other experts can be used to provide candidates. Material databases that enable the user to search for materials with specific properties can be used to quickly reach a

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[1] In some cases, product lifetimes are affected by the choice of material. If a candidate material has low environmental impacts per product but each product has a short lifetime, it is possible that the levelised environmental impacts of fulfilling the same function as the reference material are higher because they need to be replaced sooner.

[2] Ashby (1999) only considers geometric and functional constraints. Here, material constraints refer to (intrinsic) material properties or attributes, such as biobased carbon content, transparency, or eco-certification. Unlike functional constraints, material constraints are independent of the product's geometry.

[3] Note that (some aspects of) the performance of the reference product may be better than required or deliberately overengineered. Expert knowledge from product engineers can assist in identifying these cases and in setting appropriate screening thresholds/intervals.