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A life cycle framework to support materials selection for Ecodesign: A case study on biodegradable polymers

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A B S T R A C T

Nowadays society compels designers to develop more sustainable products. Ecodesign directs product design towards the goal of reducing environmental impacts. Within Ecodesign, materials selection plays a major role on product cost and environmental performance throughout its life cycle. This paper proposes a comprehensive life cycle framework to support Ecodesign in material selection. Dealing with new materials and technologies in early design stages, process-based models are used to represent the whole life cycle and supply integrated data to assess material alternatives, considering cost and environmental dimensions. An integrated analysis is then proposed to support decision making by mapping the best alternative materials according to the importance given to upstream and downstream life phases and to the environmental impacts. The proposed framework is applied to compare the life cycle performance of injection moulded samples made of four commercial biodegradable polymers with different contents of Thermo Plasticized Starch and PolyLactic Acid and a common fossil based polymer, Polypropylene. Instead of labelling materials just as "green", the need to fully capture all impacts in the whole life cycle was shown. The fossil based polymer is the best economic alternative, but polymers with higher content of Thermo Plasticized Starch have a better environmental performance. However, parts geometry and EoL scenarios play a major role on the life cycle performance of candidate materials. The selection decision is then supported by mapping the alternatives.

1. Introduction

Climate change and other environmental threats brought up in the 90's have led to a society increasingly aware to the need of a more sustainable path towards environmental preservation [1]. In fact, in the beginning of the 1990's an EPA report on life cycle design [2] claimed that often environmental criteria were not considered at the beginning of design when it is easiest to avoid adverse impacts. That decade was the turning point for a definitive paradigm changing regarding product design. Nowadays, product environmental improvement plays an important role towards sustainability [3], putting designers in a unique position to influence environmental strategy [1]. Furthermore, several authors stated the importance of design decisions in product's future impacts, being indicated that between 80% and 90% of a product's economic and environmental costs are fixed at the design stage [4].

Ecodesign, also known as Design for the Environment, Green Design, Sustainable Design, Environmental Conscious Design, Life Cycle Design, Life Cycle Engineering and even Clean Design [5], plays a crucial role in modern industry and is also becoming the main focus of the future market [6]. Ecodesign is a concept within product Design, in which environmental aspects contribute to delineating the direction of product design decisions. Considering also other traditional dimensions of analysis, namely the ones more economically or technically oriented, Ecodesign strives for developing products causing the lowest possible environmental impacts throughout the product life cycle [7]. Being a life cycle approach applied to design decisions, a limitation rises regarding knowledge in early design stages. The potential for product performance improvement is inversely proportional to knowledge about the product throughout its life cycle [3,4]. Given the high uncertainty in the design phase regarding data in upcoming product life cycle phases, estimations [8] and sensitivity analysis are usually necessary. Several tools integrating environmental regulations and data user-friendly platforms have been developed in order to overcome this limitation. Some are focused on product life cycle assessment (e.g. GaBi [9], SimaPro [10], Umberto [11]), others on material and process

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selection (e.g. CES [12]). Furthermore, in terms of cost estimations, Activity Based Costing (ABC) has been proposed by Bras and Emblemsvag [13] to address life cycle design. This approach, also named Process Based Cost Models (PBCM), efficiently compares alternative designs, allows analysing the generation of cost estimates, cost profiles and cost contributors. Moreover, it is extremely suitable when dealing with product design as it focus on correlating cost with design changes [14,15].

Material selection is an important part of product design. As Ashby [16] stated, "Materials are the "stuff" of engineering design". Therefore, Ecodesign principles should also be applied when evaluating material options. In fact, according to Field et al. [17] "the four main factors upon which the designers rely when considering materials choice are the relationship between materials specifications and technical performance of the product, the economic performance of the product, the environmental performance of the product and the practice of industrial design embedded in the product and its functionality". The increasing environmental awareness of nowadays society has affected most of industrial processes and products. Particularly plastic, one of the most versatile materials in the modern age, is widely used in many products throughout the world. However, the increase of its consumption has focused public attention on a potentially huge environmental accumulation and pollution problem that could persist for centuries, due to their lack of degradability, to the closing of landfill sites and to the growing water and land pollution [18,19]. Furthermore, as over 99% of plastics are of fossil fuel origin, their rapid increase will put further pressure on the already limited non-renewable resources on Earth. This new context of an environmentally conscious society has fostered the development of new solutions for plastics, with lower environmental impacts [20]. In fact, biodegradable and compostable plastics may serve as a promising solution to the overloaded landfills by diverting part of the volume of plastics to other means of waste management and, in most of the cases, by preserving non-renewable resources [21]. Thermo Plasticized Starch (TPS) has been seen as a possible substitute for petroleum based plastics as it is both renewable and degradable. However, due to its water sensitivity and low mechanical properties, it's not suitable for many plastic products. One solution developed to overcome these limitations was to combine plasticized starch with another biodegradable polymer [22,23]. PolyLactid Acid (PLA) is currently one of the most promising biopolymers, with good mechanical properties, thermal plasticity and biocompatibility, being a promising polymer for various applications [24]. In fact, some studies have found that PLA has comparable mechanical and physical properties to that of Polytethyleneterephtalate (PET) and Polystyrene (PS) [25,26], therefore being able to fulfil very different commercial applications [22,27].

This study proposes a comprehensive life cycle framework to support Ecodesign in material selection. It is clear the need to evaluate in design decisions both costs and environmental impacts throughout the product life cycle. Our proposal is to use process models to feed the required data. By modelling all processes in each stage of the product life cycle, it is possible to generate the inputs for Life Cycle Cost (LCC) and Life Cycle Assessment (LCA) models, and so to evaluate the life cycle economic and environmental performance of alternative materials. These alternative materials are the options already limited by product logic, specific requirements or other material selection methodologies (e.g. material property charts). The comprehensive analysis is then focused on the technically suitable and most promising material alternatives. A case study is also presented regarding the performance evaluation and comparison of four different types of commercial biodegradable polymers (BDP) with different amounts of TPS and PLA content and a common fossil based polymer, Polypropylene (PP) considering samples produced by injection moulding.

2. Life cycle framework

The framework proposed in this paper is composed by several consecutive and interacting blocks of information and computing tools. It begins with the definition of the analysis scope for each part, in which the alternative materials and life cycle stages to analyse are defined, as well as the processes included in each phase. The subsequent step is to model each process using process-based models (PBM), derived from the process-based cost models (PBCM). Usually used for cost modelling, the PCBM approach is proposed to model also environmental resources consumption and emissions as most of them are simultaneously cost and environmental drivers. The processes involved in each life cycle stage are therefore modelled in order to compute the resources requirements and, further on, the costs and environmental impacts. This is a demanding task, as a significant number of manufacturing technologies can be involved in the process, and furthermore the relations between part design and the technological requirements along the process need also to be considered. For this task engineering knowledge of each technology in the process is required, as the modelling is not simply a cost or environmental accounting procedure.

PBM starts from the description of the intended product (part(s) material(s) and geometry(ies)). The process(es) involved in production is(are) then modelled regarding the sequence of steps, cycle time, resources (equipment and labour) requirements and specifications, etc. This can be obtained with theoretical and empirical relations correlating the properties of the part and the requirements of the involved technologies. By adding inputs regarding the operating conditions of a certain plant it is possible to build up the operations description, which allows computing the needed resources regarding the number of tools, equipment, operators, etc. (or, as far as equipment and operators might not be dedicated, the time allocated to the product being analysed).

The integration of additional relations correlating consumptions/resources time use and design features may be relevant to further explore critical aspects. These are for example models to estimate tooling reliability and maintenance performance and energy as a function of part geometry and material. The need to develop them depends on several aspects, namely the processes involved and the design alternatives. For example in energy intensive processes with high variations of power use over a production cycle (e.g. plastic injection moulding) it is essential to model efficiently the energy consumption.

Having defined the scope and modelled all the processes it is possible to compute the required resources to produce the part(s) for each alternative material option. The deep level of process parameterization of the PBM based tool permits a myriad of sensitivity analysis forming a bloc of information that will be used as input for the LCC and LCA analysis – the third step. Therefore the third step is to include price factors to each cost driver to assess the economical performance of an alternative throughout the life cycle. In parallel, an impact assessment is also performed to the data inventory retrieved from the PBM to assess the environmental performance. The life cycle impact assessment (LCIA) phase connects the inventory data with the environmental impacts. In this study, the main objective in performing this step is to have a global quantitative result of each alternative, similarly to the cost dimension. Several methods are available nowadays and two main types exist: problem (e.g. CML 2002) and damage oriented methods (e.g. Eco Indicator 99) [28]. The first model the impacts at a midpoint somewhere in the environmental mechanism between emissions and damages to minimize uncertainty. The second model the cause