Environmental challenges when developing renewable materials to replace non-renewable materials - guidance from LCA studies

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Abstract

Since the demand for more sustainable products is growing, the pressure on material developers to improve the sustainability performance of the products that they are developing is increasing. As a consequence, the need to move away from a narrow understanding of "product" and "environment" is becoming more apparent. A Life Cycle Assessment (LCA) approach has been used to find rough estimates of how much process energy, raw materials etc. are used in the process of transforming a biomass feedstock into a new material. A reference product with a fossil based material intended to be replaced is used as a benchmark for the new product. The new product must perform at least as well as this benchmark and preferably better. We illustrate this LCA based methodology using the example of replacing petroleum-based polymeric material with wood-based material in a disposable consumer product.

Keywords: Life cycle assessment, product development, material, renewable, environmental window of opportunity

1. Introduction

For several reasons such as resource limitations, expected price development and climate concerns, human material and energy demands need to shift from fossil to renewable resources. However, it is vital in this process to also consider constraints in ecological productivity, limited by e.g. access to land area and water, as well as other concerns that relate to the production or handling of biomass resources. So far, evaluations of shifting from fossil to renewable resources have primarily been made for transport fuels [1], e.g. crops for bio-ethanol production, but the same general issues are relevant also to the shift from fossil- to biomass-based materials. In countries with large forested areas, efforts to develop wood-based materials to replace petroleum-based materials, such as polymers, are often justified based on arguments related to the environment, economy or security-of-supply. However, statements in this direction are seldom based in quantitative assessments, especially not regarding long term consequences for environment, current users and other stakeholders around the material resource.

One technical route for replacing petroleum as a resource base for polymers is through chemical processing of wood or other biomass, breaking down cellulose and other constituents into chemical precursors like synthesis gas or ethylene, and then proceeding along traditional process routes into polymeric materials [2-3]. Another route is to utilize and if necessary modify properties of wood constituents in order to create new materials that build on existing complex chemical structures with particular properties that can serve a specific function in a product [4-6]. Building on structures that nature creates demands less modification but more separation of unwanted materials.

A biomass-based material is not inherently better in all aspects compared to a fossil-based material [1]. Therefore, a pure focus on shifting to renewable resources might not be enough but the entire life cycle needs to be assessed [12]. It is therefore important to ensure that new materials are assessed for their sustainability performance irrespective of resource base utilised.

2. LCA as guidance in product development

Environmental and other sustainability considerations should start influencing the product development process as early as possible i.e. in specification and goal setting in early product development phases, otherwise only small changes to the product design are possible [7]. However, in product development the final production system is not yet defined. In other words, no measured data for the processes and other parts of the system are available and therefore estimates need to be used in LCAs (Life Cycle Assessments) and other assessments.

2.1 Rules of thumb in process/material selection

Today LCA is mainly used in product improvement and development in two ways [8]. The first is by quantifying and evaluating the largest environmental impacts along the entire life cycle of existing products, thus identifying environmentally important design variables. The result is then used to decide how the product can be improved in terms of its environmental performance, sometimes in the form of rules of thumb. An example is the general LCA consensus that the largest environmental impact in the life cycle of a car is the use stage, which provides the rule of thumb that reducing weight will significantly increase environmental performance [9]. The second common way to use LCA in product development is to assess proposed changes. An example could be changing a process, a part or a material and consider the estimated LCA result of that change by a so called "quick and dirty" comparative LCA [10]. By "picking the winner" it is possible to suggest appropriate ways to modify or design a system in order to decrease its overall environmental impact.

However, with the two above approaches we are stuck with choosing among existing technologies. That is, products are improved and managed, not developed to fit emerging demands from customers or long-term needs of society. Also, the assumptions made in the LCA do not often involve knowledge and experience of product development but are made by the LCA expert based on his/her knowledge and access to data.

2.2 Environmental window of opportunity

The product or material development team's creativity, experience and knowledge can be utilized in improving the environmental performance of a product or a process by presenting LCA results showing the environmental window of opportunity early on in the development process. This means visualising estimates of how large the flows of process energy, raw materials or other potentially important parameters can be for new processes if the new alternative shall be preferable. For example, when planning for a shift from a fossil-based to a biomass-based material, it is important to understand under which conditions this shift will actually lead to a more sustainable product. This assessment is in itself difficult to perform since it depends on things like assumptions about the future and effects in remote parts of the product system. Furthermore, it depends on which aspects are assessed and how these are weighted against each other. Nevertheless, relatively simple back-of-the-envelope calculations visualised for the development team can provide important guidance even at very early development stages and stimulate the creativity of the development team. An example of how these visualisations can be used in guiding development efforts is presented in the following case study.

3. Example: LCA of a wood-based diaper

Chalmers University of Technology is engaged in a research project with a specific focus on using modified wood fibres to replace petroleum-based absorbent material in a diaper and ensuring that the new diaper is also more sustainable than the reference diaper [11]. The wood fibre, fluff pulp, which is the wood-based material used in the reference diaper is the base for the material development. This project handles Nordic wood resources and wood-based material production together with a European market. The hypothesis when setting up the project was that replacing petroleum-based material with modified fluff pulp would make the product more sustainable. A weighting is also necessary in order to deal with trade-offs when comparing different kinds of impacts. For example, sustainability impacts related to the use of petroleum materials such as resource scarcity, risk of oil leakage to nature and greenhouse gas emissions will need to be compared with impacts related to increased use of biomass resources such as land use and loss of biodiversity and recreational space. A change of material may interact with all stages in a product's life cycle because a new material seldom has exactly the same properties as the one it is to replace. Therefore, changes may occur in other life cycle stages than material production or in background processes. In our example, how a new material will influence the use stage and waste management is not yet known.

Fig. 1 shows results of a preliminary cradle-to-grave LCA estimation of the reference diaper with its petroleum-based absorbent compared with two extreme cases exemplifying low and high wood use in a new wood-based material. To get around uncertainties in future product systems, the cases represent two hypothetical products, assumed to result in the same absorption performance as the reference. These form the upper and lower limit of the window of opportunity for these two extreme cases. These first calculations are based on data from an existing product with quick estimates made in order to provide early indications on potential opportunities. In the high wood case, fluff pulp has been added equal to twice the weight of the eliminated petroleum-based absorbent material. This results in a heavier product. For the low wood diaper case, all petroleum-based absorbent has been removed assuming no loss of absorption capacity, i.e. the wood-based material already present in the diaper has been assumed to be improved through material development so that increased absorption capacity counteracts the loss of the petroleum-based absorbent. The low wood case would therefore result in a lighter product.

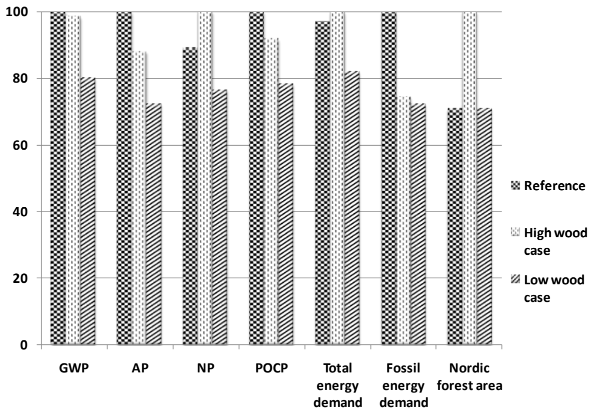

Fig. 1: Cradle-to-grave LCA estimation of diapers – the reference diaper is compared to high and low wood cases, presented as percentage relative to the highest contributor [13-14].

In both the low and the high wood cases, the production process transforming fluff pulp into a new material is disregarded. Therefore, Fig. 1 can be used to show the window of opportunity for the material development in terms of selected environmental impacts. Environmental impacts from the production process of the new material can thus not be allowed to be much higher than present fluff pulp production, if the new material is to be a more benign alternative than the reference material. The high wood case even has a higher environmental impact for three of the shown impact categories. This indicates the challenges involved in the material development process. Petroleum-based absorbents typically represent about 33% of the weight of diapers [15]. The material developers for the petroleum-based material have over a long period of time successfully worked on environmental optimisation of their processes and on improvement of the material properties. What is needed in order to replace this material is not only a new material from a renewable resource but also a new material that requires less resources in general, including chemicals and energy. Alternatively, material innovation is needed, that gives higher performance to the new material or even additional functions that can be part of a new and improved product concept.

Except for the 'Nordic forest area', the parameters presented in Fig. 1 are classical LCA parameters for this type of product and industry. It could be argued that other parameters might be of relevance, such as health effects [16] or water consumption [17]. This is particularly true if international comparisons are to be made with products from regions with different environmental regulation or different climatic factors.

The parameter 'Nordic forest area' for raw material supply is a simulation that has been used to guide the material development process in the described project. Obviously, the high wood case demands more biomass and thereby more forest area. A classical challenge in the application of LCA to the design process is how to compare products that have environmental impact peaks in completely different areas, like for example the high wood case in Fig. 1, which uses more forest land area but less fossil energy, whereas the reference case uses less forest land area but more fossil energy.

As product development progresses, more data becomes available. In this project, early estimates of material production parameters became available and could roughly be translate into LCA impacts. Fig. 2 illustrates the cradle-to-gate LCA of the present petroleum-based absorbent material, a regular fluff and a modified fluff pulp intended to replace the petroleum-based material. However, the material properties and the material's function in the product are still not known. If the modified fluff pulp from Fig. 2 is assumed to be used in the high wood case described earlier (i.e. twice the weight of the replaced petroleum-based absorbent and same amount of fluff pulp), it results in a worse product environmental performance compared to the reference product in all impact categories except for POCP. Performance in terms of energy demand (total and fossil) becomes particularly poor. Therefore, a special effort will be made to improve the energy efficiency of the modified fluff pulp in the described project. Since Fig. 2 shows only the cradle-to gate analysis of materials and Fig. 1 a cradle-to-grave analysis of products, these are not directly comparable.

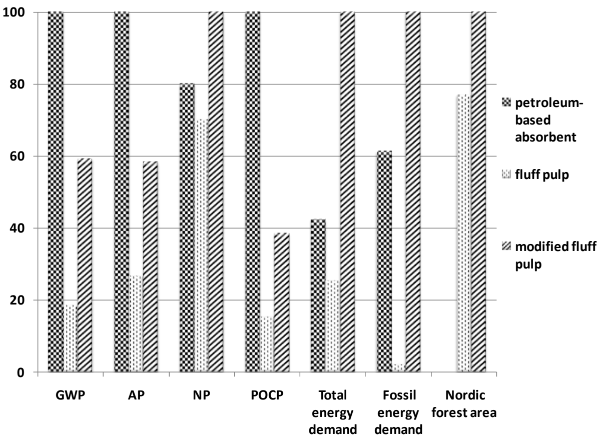

Fig. 2: Cradle-to-gate LCA results for petroleum-based absorbent material, fluff pulp and modified fluff pulp presented as percentage relative to the highest contributor [13-14].

Fig. 3 shows the environmental impact of the reference diaper divided into different life cycle stages. This graph was presented at the start of the project. It shows that the impacts embedded in the materials are the main contributors to the environmental impacts. For the materials both resource acquisition and material production is included. The diaper packaging, diaper assembly, transport, use and post use waste stages have comparatively low impacts. Therefore, in this project, material innovation that results in an improved environmental performance in the resource acquisition is a priority. However, environmental impacts in Fig. 2 demonstrate that changing to renewable resource has small potential to lift environmental performance and impacts in production probably will increase due to extended energy use. Consequently, if the results from Fig. 2 and Fig. 3 are connected it seems rather difficult or even impossible to reach the goal of a more sustainable product. Therefore, we need to aim for material innovation resulting in an enhanced total environmental performance i.e., additional functions, features that can be part of a new and improved product concept are necessary.

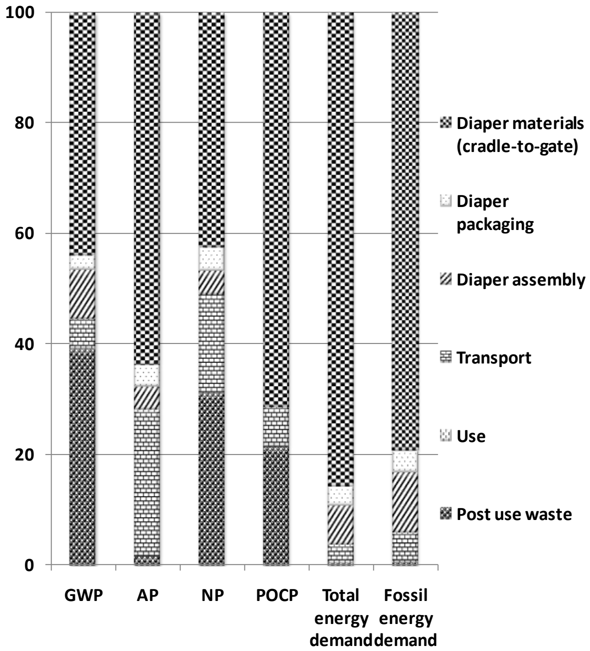

Fig. 3: Environmental impact of the reference diaper divided into four life cycle stages, as a percentage of total impacts, for four commonly used impact categories [13-14].

In the described research project, LCA results like the ones in Figs. 1 - 3 have been discussed at project meetings and workshops in which the whole material development team has participated. The workshops were used to involve the material development team in broader system thinking aimed at integrating their knowledge and experience with an understanding of potential sustainability consequences in order to generate more sustainable ideas. The workshops were also used to identify connections between sustainability impacts and material properties the material development team is more used handling, like absorption capacity, fibre length and chemical bonding. When developing a material that is intended to replace another, it is important to understand what specific material properties that are needed in order to deliver the desired function. It would be counterproductive to copy all the properties as not all of them help in delivering the function of the product. Instead, focus should be on material parameters giving the desired function, and how these affect the environmental performance in different life cycle stages of the product. For example, what material properties could improve the function so that less material is needed in the product or what added feature in the material will result in a decreased impact in the waste management.

4. Discussion

In early phases of material or product development, the production processes are often unknown, like the location of production facilities, the mass of material in the final product, what equipment will be used and many other things. Therefore a scaled-up model of the process is sometimes used for generating estimates of input parameters for an LCA. Resistance may be encountered to the use of preliminary process estimates for environmental assessments when material design has not yet progressed past the bench-test scale. Results can be seen as threats to innovation if they become unfavourable. Nevertheless, such preliminary calculations are important in the development of more sustainable products. Models and estimates will continuously be improved during the project when more is known. It is important to only use these early LCA results as indications based on coarse assumptions and not be lured into seeing them as the last word on the product's environmental performance.

The case study reported on here illustrates how LCA can be used at early material development stages in order to guide development towards sustainability. It also shows the great challenges that may be involved when shifting from a petroleum-based to a wood-based material.

5. Conclusion

Developing materials for more sustainable products is a difficult issue. It requires not only a shift to renewable resources or an environmental optimisation of material production processes but also reducing resource use while retaining or improving product function. This demands the material development team's awareness of important sustainability considerations. Visualising environmental aspects of sustainability can be done using results from simple LCAs, showing e.g. the environmental performance of different life cycle stages and environmental impacts of different materials. Analysts should think creatively about how existing data can be used to illustrate the environmental window of opportunity and challenges for products that have not yet been designed.

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