THESIS FOR THE DEGREE OF LICENTIATE OF PHILOSOPHY

Guiding the development of wood-based materials towards more sustainable products

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CHALMERS UNIVERSITY OF TECHNOLOGY
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For Mum

ABSTRACT

In order to stay in business in the long term, companies need to develop more sustainable products. This creates a demand for ways to influence product sustainability at the early stages in product development. This has been studied through literature surveys and action research carried out within a materials development project, with the aim of developing wood-based materials to replace petroleum-based materials while ensuring a more sustainable final product.

An analysis of available sustainability impact assessment tools relevant for the material development project showed a lack of ready-made assessment parameters for comparing different types of limited resources, like petroleum, land area and water, and that approaches to establishing relevant sets of assessment parameters that provide for the specific circumstances of a project are missing.

A team-learning process for establishing a case-specific set of product sustainability assessment parameters was developed. The set of parameters is intended to guide through the product development process as well as be a basis for a sustainability comparison of a new product with a current product. The process emphasises that in order to develop more sustainable products, the team working with material or product development must be aware of which surrounding world and future-oriented factors that may have significant impacts on the specific product's sustainability performance. The process suggests that a relevant set of parameters needs to be developed and then translated and integrated into each team member's everyday work.

Various activities were performed within the project to provide input to the development of the process as well as to provide input to the assessment itself. Experiences from such activities emphasise the challenges involved in interacting with the development team, e.g., in terms of motivating the team and providing meaningful information to the team.

Keywords: Sustainability assessment, material development, product, team learning

LIST OF INCLUDED PUBLICATIONS

Paper I

"Changing from petroleum to wood-based materials: critical review of how product sustainability characteristics can be assessed and compared"

Gunilla Clancy, Morgan Fröling and Magdalena Svanström
Published in *Journal of Cleaner Production* 39 (2013) 372-385

Paper II

"Insights from guiding material development for more sustainable product"

Gunilla Clancy, Morgan Fröling and Magdalena Svanström
Submitted for publication

Paper III

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

Gunilla Clancy, Morgan Fröling, Gregory Peters and Magdalena Svanström
In proceedings of *9th International conference on EcoBalance 'Towards & Beyond 2020'*, 9-12 November 2010, Tokyo, Japan

LIST OF RELEVANT INTERNATIONAL CONFERENCE CONTRIBUTIONS

A. "Sustainability considerations in early phases of product development: The wood-based diaper" Gunilla Clancy, Magdalena Svanström, Morgan Fröling, Ellen Riise and Elisabeth Carlsson. Oral presentation. Extended abstract in proceedings of SETAC Europe: 19th Annual Meeting *'Protecting ecosystem health: facing the challenge of a globally changing environment',* 31 May 31- 4 June 2009, Göteborg, Sweden

B. "Comparing the sustainability of using a non-renewable oil-based material in an absorbent hygiene product with that of using a renewable wood-based material" Gunilla Clancy, Magdalena Svanström, Morgan Fröling, Ellen Riise and Elisabeth Carlsson. Poster presentation at the Eforwood conference *'Shape your sustainability tools - and let your tools shape you',* 23-24 September 2009, Uppsala, Sweden

C. "The ageing society: An example of consequences for biomass use" Gunilla Clancy, Morgan Fröling and Magdalena Svanström. Oral presentation at the MFA-ConAccount Meeting *'MFA for Sustainable Future'*, 7-9 November 2010, Tokyo, Japan. Conference abstract corresponds to Appendix A in this thesis.

D. "Environmental challenges when developing renewable materials to replace non-renewable materials: Guidance from LCA studies" Gunilla Clancy, Morgan Fröling, Gregory Peters and Magdalena Svanström. Oral presentation at the biennial conference EcoBalance *'Towards & Beyond 2020',* 9-12 November 2010, Tokyo, Japan. Conference paper is attached as Paper III in this thesis.

E. "The ageing society: An example of consequences for biomass use for incontinence diapers in Europe" Gunilla Clancy, Morgan Fröling and Magdalena Svanström. Poster presentation at the AGS Annual Meeting *'Sustainability and Change'*, 23-25 January 2011 at Chalmers, Göteborg, Sweden

F. "Approach to establish relevant sustainability assessment parameters in product development" Gunilla Clancy, Morgan Fröling and Magdalena Svanström. Poster presentation at the 6th ISIE Conference *'Science, Systems and Sustainability'*, 7-10 June 2011, Berkeley, San Francisco, USA

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Göteborg, Sweden 2012

Gunilla Clancy

TABLE OF CONTENTS

1. INTRODUCTION

Our planet has limitations, as can be seen from, e.g., discussions on the ecological footprint, in which the pressure that human demands put on the biosphere is measured in the number of planets required to regenerate the consumed resources and assimilate the waste generated followed a given lifestyle (WWF 2011), or in discussions of planetary boundaries (Rockström et al. 2009). The demand for the planet's resources is increasing due to economic growth and population growth, combined with intensive use of energy and materials. To continue using our planet's resources in the long term requires restrictions on resource use but also restrictions on pollution to prevent harm to ecosystem services that are needed for resource regrowth (MEA 2005). As pollution can travel far, these are global issues and in order to manage these in an equitable way, global political incentives and global cooperation are needed. Since resources are needed for most products, global activities have an impact on the life cycles of products and need to be considered in material and product development.

Global activities are part of 'Sustainable development', which is a term used in many different situations, in politics, in business strategies, in advertising and in other discussions. When hearing all these politicians, scientists and company leaders talk about sustainability, it is tempting to believe that sustainable development is a well-defined and established plan for a future sustainable society that everyone agrees on and is striving to implement. Yet, sustainable development is far from a clearly described concept.

Companies, thus, need tools to describe sustainable development in relation to their own businesses and to formulate and integrate long-term strategies and visions for sustainability. These strategies for reducing negative sustainability impacts of a company and their products should preferably also aim at the product development stage since many of the sustainability burdens of a product are determined through choices that are made at this stage, and at this stage, the cost of change is comparatively low (Ramani et al. 2010).

1.1 Aim of the thesis

The aim of the research presented in this licentiate thesis is to suggest an approach for establishing relevant sustainability parameters and to point out specific challenges in assessing sustainability when changing from petroleum-to wood-based materials in an adult incontinence product. The set of identified parameters is aimed at guiding the development of materials intended for the product as well as being a basis for a sustainability comparison of the new product with a reference. The research question is:

How can product sustainability assessment be performed in material development towards a more sustainable adult incontinence product?

This research was carried out within a material development project. The project is a research collaboration between two companies and Chalmers University of Technology and was funded by Vinnova and the two companies. The writing of this thesis summary and Paper II was, however, funded by Chalmers University of Technology. The research collaboration has a specific focus on developing wood-based materials that could potentially replace non-renewable materials in an adult incontinence product, while ensuring that the new product is also more sustainable than the reference product. Six different sub projects focus on areas such as forming networks of fibres with tailored properties, characterisation of the networks, and designing the production process. This research was part of the sub project that focused on assessing the sustainability of the life-cycle of the adult incontinence products and guiding the material development process towards a more sustainable final product. The material development team consisted of graduate students, their supervisors and senior researchers from the two companies.

1.2 Research design

Before approaching the overall goal of assessing the sustainability of an adult incontinence product, some issues needed to be clarified or studied further. This was done mainly through literature studies. First, a description of what is meant by 'sustainable product' was needed. Second, how to handle sustainability assessment early in product development needed to be studied and decided on, and third, how product sustainability is assessed today needed to be reviewed with a specific focus on the assessment and comparison of the use of petroleum and wood resources.

Apart from literature surveys, action research was applied in the project in order to provide input on opportunities and difficulties in guiding product development towards a more sustainable product. Action research means that the researcher takes part in a project and tries to change or improve something in the on-going project (in this case guiding towards sustainability) and at the same time observes what is achieved and the outcome. Action research involves utilising a systematic cyclical method of planning, taking action, observing, evaluating (including self-evaluation) and critical reflection prior to planning the next cycle (Wadsworth 1998).

1.3 Guide to readers

This summary of the thesis includes overviews of Papers I to III, listed in the beginning of the thesis and printed in full after this thesis summary, and additional relevant literature, analyses and experiences from work in the research project.

Chapter 2 gives a summary of (1) what sustainable development implies based on descriptions in literature, (2) how products' sustainability is assessed today, (3) sustainability considerations in wood resource use, and (4) examples of efforts to integrate sustainability into product development. During the research, three often unstated points of departure in assessing sustainability in product development became explicit; these are presented in Chapter 3.1. Based on the gained understanding from literature surveys and work in the project, a sustainability assessment method was developed that utilises a team-learning approach with the aim of achieving a greater awareness in the team of important sustainability aspects in the specific material or product development project. This approach is presented in Chapter 3.2. Experiences from using elements of the approach in the material development project are described in Chapter 4. Conclusions are presented in Chapter 5. The acquired knowledge and experiences provide the basis for the recommendations for future research presented in Chapter 6.

The scopes of the appended papers and their relation to each other and this thesis are illustrated in Figure 1. In order to get external feedback on the research, it has, on a number of occasions, been presented at international scientific conferences. A list of such conference contributions (A to F) is listed in the beginning of this thesis, and referred to in this thesis summary when relevant.

A literature survey was carried out on sustainability assessment tools used today with emphasis on assessment parameters for comparing petroleum and wood as material resources. This survey was contrasted with the needs in the project, and the existing gap in knowledge was evaluated and further steps that needed to be taken were identified. Results from this part of the research work are presented in Paper I and in conference contribution B. Additionally, a list of sustainability aspects and parameters found in literature that are relevant to the project was compiled and is attached in Appendix B.

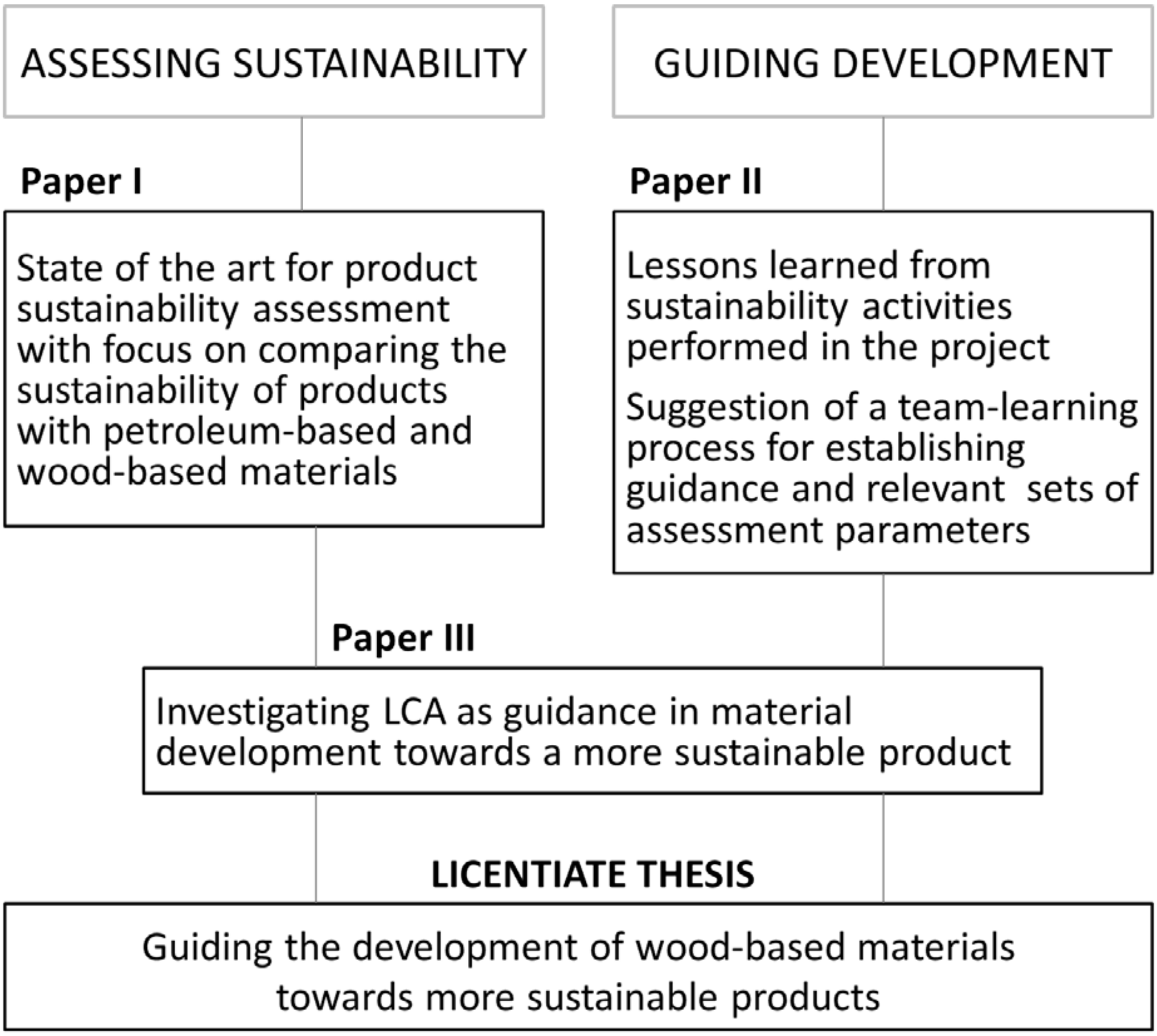

Figure 1. *This licentiate thesis discusses the guiding of development of wood-based materials towards more sustainable products. The research has been carried out through a number of smaller studies on assessing sustainability and on guiding development.*

To gain a deeper understanding of the requirements and barriers in guiding product development towards a more sustainable product, experiences from work performed in the project were analysed and complemented with a new literature survey. The work resulted in a team-learning process for establishing sets of relevant product sustainability parameters, as described in Paper II and in conference contribution F. An early version of the process is described in conference contribution A.

In one of the efforts to guide development within the project, a Life Cycle Assessment (LCA) approach was applied to visualise the environmental challenges in early phases of the material development work. This effort is presented in Paper III, and in conference contribution D. Another effort with the goal of visualising challenges in material development was a calculation of biomass need and thereby forest area need for adult incontinence products in Europe from 2010 to 2050. This effort is presented in Appendix A and in conference contributions C and E.

2. SELECTED RESULTS FROM LITERATURE STUDIES ON SUSTAINABILITY ASSESSMENT IN PRODUCT DEVELOPMENT

This section provides an overview of relevant literature and discusses selected literature survey results in connection to the research project. For a review of the assessment of the sustainability of petroleum- and wood-based materials, see Paper I.

2.1 Describing sustainable development

There is general agreement in society on the need to move towards a more sustainable society. However, how this is to be done and what the more detailed goals should be is viewed differently. Furthermore, depending on the specific situation, different sustainability aspects may be more or less urgent or important to consider. The most common description of sustainable development is the one from the World Commission on Environment and Development, often called the Brundtland definition:

> *Humanity has the ability to make development sustainable – to ensure that it meets the needs of the present without compromising the ability of future generations to meet their needs. (WCED 1987)*

This definition is very general and thereby it is a concept that everyone can agree on. However, what sustainable development means in practice, as for a specific product, cannot be described in generic terms (Kates et al. 2005, Mitchell et al. 1995). Consequently, the essence of the definition needs to be applied in making case-specific descriptions of sustainability.

Human needs

The Brundtland Commission's definition of sustainable development states that human needs of present and future generations must be fulfilled. Therefore, one question that must be addressed when defining what is a more sustainable product is how to describe "human needs". The Chilean economist Manfred Max-Neef has identified nine fundamental human needs (Max-Neef 1989): subsistence, protection, affection, understanding, participation, leisure, creation, identity and freedom. Max-Neef states that these needs are the same for all people regardless of generation, gender, education, religion or geographical location and that these fundamental human needs cannot be substituted for one another; a lack of any of these represents a poverty of some kind. There is, however, one need that is absolutely vital for survival, the minimal amount of nutrition and water that a person needs, termed subsistence. Max-Neef states that what differs between cultural contexts is *how* such basic needs are satisfied and not the needs as such. This model, that describes nine fundamental human needs, can be useful in defining a 'sustainable product', i.e., in considering the relation between the fulfilment of human needs and the function of the product and other social impacts throughout the product's life cycle. Other models or descriptions of human needs exist, for example, in the well-known theories by Maslow (Maslow 1943) or the more recent model used in the Millennium Ecosystem Assessment (MEA 2005). Human needs are also central in related concepts, like Quality of Life (Costanza et al. 2007). In this project, the impact of the product on the stakeholders' quality of life is of interest. Examples of stakeholders are the user, the carer, the developer, the material producer, the product manufacturer, the seller, the purchaser, the media, the government and the forest owner. Quality of life considerations vary depending on the stakeholder. For the material producer, it could be about impacts on safety and health, for developers, it could be the competence development of co-workers, and for users it could be satisfactory product function.

Long-term considerations

The Brundtland definition of sustainable development is based on the principle of intergenerational equity and thereby requests that the ability of future generations to meet their needs is considered. For product development, this implies that companies need to have a long-term strategy in order to avoid moving in an unwanted direction and to avoid creating lock-in effects in unsustainable systems by investing in development and assets that they ultimately need to shift away from (Hoffrén & Apajalahti 2009, Westley et al. 2011). An important feature of any product, therefore, is that it has the potential to fit into a sustainable society, or at least be a bridging solution that can assist in a move in the desired direction. A long-term perspective is needed in which not only today's major challenges are included but also potential upcoming future challenges. Such challenges can be estimated by identifying unsustainable trends in, for example, consumption and the availability of resources and by attempting to anticipate critical incidents that may alter the situation. As a basis in such an analysis, the four universal and time-neutral sustainability principles proposed by John Holmberg and Karl-Henrik Robèrt around 1990 can be used (Holmberg 1998). The principles have been worded differently but nevertheless have the same basic meaning. Here follows one of the first versions.

In order for a society to be sustainable, nature's functions and diversity are not systematically:

1) subjected to increasing concentrations of substances extracted from Earth's crust;
2) subjected to increasing concentrations of substances produced by society;
3) impoverished by over-harvesting or other forms of ecosystem manipulation and
4) resources are used fairly and efficiently in order to meet basic human needs worldwide

Companies, to a greater extent than today, need to define their visions and strategies with a long-term perspective in mind *and* communicate the strategies to their product developers in order to manoeuvre company activities through issues like anticipated resource and policy restrictions (Baumann et al. 2002). Strategic companies can turn this into market advantages. However, technology development is often very costly, especially in the initial phase and, therefore, many companies do not have the means to be too far ahead of others since the cost for, e.g., developing materials for new product areas is high. On the other hand, to lag behind in development might result in unsellable products and penalties that can become very costly for a company. Companies need to balance their development in suitable ways according to their circumstances, like company size, available cooperation and type of product. One decision a company needs to take is if *repair*, so called end of pipe solutions, and *refine*, i.e., improvements in products and processes, are sufficient or if *redesign* or even *rethink* is also needed to remain in operation in the long-term.

2.2 Assessing product impact on sustainability

A practical philosopher, Munthe, in a report to the Swedish Agricultural Administration (Munthe 1997), lists three questions that should be answered before any assessment in order to assure transparency and to avoid influences from expected or wanted results:

- What should be included in a concern?
- How should any trade-offs between concerns be made?
- How should uncertainty in necessary information be handled?

Since the same type of questions have also been highlighted for comparing products (Steen 2006), they are most likely useful as a basis for any product assessment. The three questions can be formulated in the following way for this project: 1. What sustainability characteristics are essential to consider in the product assessment, taking into account the specifics of the product systems under study and the challenges that emerge in light of sustainable development, i.e., which assessment parameters are the most relevant? 2. How should potential trade-offs between these sustainability concerns be made when the compared sustainability profiles have peaks in different areas? and 3. How should uncertainties in the product sustainability assessment be dealt with in terms of, for example, unknown characteristics of the developing product system and of future society?

A diverse number of tools that can assess different attributes of product sustainability for parts of or whole product life cycles exist, like LCA (Life Cycle Assessment), Ecological footprint and SocioEcoEfficiency Analysis (SEEbalance). Paper I contains a summary table of elements found in different methods that can be of use in a product sustainability assessment throughout the material development in a project. The table shows that there are different methods available but that these methods are normally only suitable for comparing similar types of products or similar sets of impacts. There is a lack of frameworks for dealing with sustainability impacts that are fundamentally different in character. One example is the comparison of using renewable and non-renewable resources, which none of the methods can handle satisfactorily. The methods mainly rely on quantitative data, thus, preferably assessing existing products with defined product systems. Since product sustainability assessment parameters need to be selected on a case-to-case basis, a 'method' for sustainability assessment must include an approach for how to establish assessment parameters for each specific case and their relative weights. Consequently, the project in this research has no ready-to-use assessment tool.

2.3 Aspects and parameters describing product sustainability

As discussed earlier, sustainability aspects and parameters need to be selected based on the circumstances in each specific case, and be aligned to the case-specific description of sustainability. Otherwise, aspects selected might be counterproductive, for example, might miss product functionality, go against strategies in industry/government or steer towards desired, often short-term, results and thereby probably miss opportunities for the product to be competitive in the future. However, a list of suggested assessment parameters can be useful, but may give the false impression that the list is appropriate. None of the described methods provide guidance on how parameters should be selected and, when needed, developed. For some areas, for example the utilisation of non-renewable and renewable resources, there is a lack of assessment parameters that sufficiently describe current concerns. There is a particular lack of parameters that describe the competition for renewable resources; for example, how an increase in renewable resources for energy interacts with food and material production.

For the needs of this research project, there is a lack of parameters that describe potentially important sustainability considerations in a comparison of the use of wood or petroleum as the raw material in the product. Such considerations would include social impact, impacts on ecosystem services, such as biodiversity and competition for different types of limited resources like petroleum, land area and water, see Paper I.

In this research, sustainability 'aspect' is the term used to describe a concern that may have an impact on product sustainability, such as depletion of non-renewable petroleum resources, or impact on culture and recreation. The term 'aspect' is also used in ISO standards, for instance, in 'Environmental management: Integrating environmental aspects into product design and development' (ISO/TR 14062 2002), and in Environmental management: Vocabulary, 'Environmental aspect' is defined as an element of an organization's activities, products or services that can interact with the environment (ISO 14050 2009). Others, e.g., the patent 'Product sustainability assessment' (Warther & Rebitzer 2008), uses the term 'criterion' instead of 'aspect' for similar things. One reason why 'aspect' is chosen instead of 'criterion' is that the incontinence product dealt with in the project is purchased via procurement, and in procurement, 'criterion' is used in another context, namely as the level of each aspect that is required. For examples of sustainability aspects, see Figure 2 and Paper I. An aspect can be described by several 'parameters', a 'set of parameters'. It is believed that one parameter is not enough, but rather a set of parameters is needed to describe an aspect.

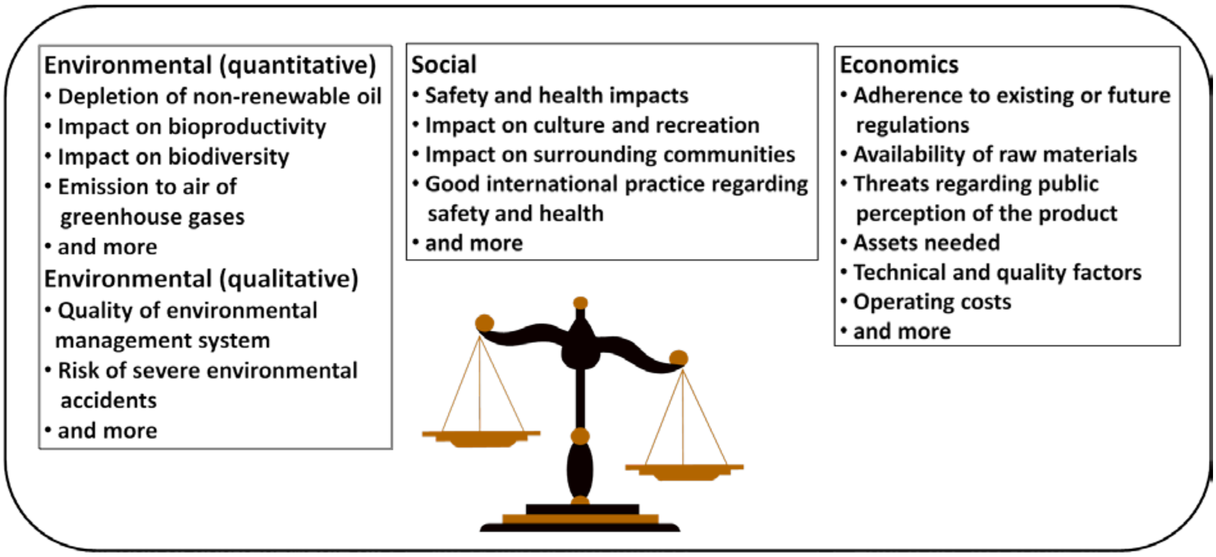

Figure 2. *Examples of sustainability aspects discussed in literature. The figure was part of conference contribution B.*

When looking for relevant sustainability parameters in literature, a list containing 40 sustainability aspects and 500 sustainability parameters was compiled, see Appendix B. The list also shows references to literature discussing each sustainability parameter and, if applicable, case studies applying the sustainability parameter. The list shows that there are few case studies that have applied the different suggested sustainability parameters. None of the sustainability parameters can by themselves describe the complete sustainability performance of a product, but they can all provide input to a sustainability assessment.

There are many challenges to selecting or developing appropriate parameters for an assessment. Many ecological and social sustainability aspects exhibit non-linear behaviour, and are non-substitutable and/or impossible to translate into the same types of units. Losses, e.g., in terms of biodiversity and cultural diversity, can be irreversible. Furthermore, several natural resources are multi-functional, e.g., forests can provide both raw material for human society and shelter to animals, absorb $CO_{2,}$ and regulate the flow of rain water.

To avoid missing important sustainability considerations when reducing the description of product sustainability down to relevant product assessment parameters, a holistic and future-oriented perspective is needed. However, today, a holistic and future-oriented perspective is only rarely applied by scientists. Instead, the mindset is rather reductionist, reducing the wholeness to individual parts and bits to make them understandable. The notion is that parts explain the whole, and that objectivity is an accepted given truth of well performed scientific work. Bell describes this thinking as follows:

> *A reductionist approach rejects ideas about the reality and importance of unscientific aspects of life (hunches, guess-work, instincts for rightness and even, in certain circumstances, illogical activity – i.e. activity which is not consistent with narrow definitions of efficiency). The universe is seen through empiricism as fixed, knowable, measurable and therefore, predictable. (Bell 1996)*

Based on the awareness that reductionist thinking is widespread, Bakshi and Fiksel conclude that achieving sustainability requires engineers that are trained to adopt a holistic view of processes and to recognise that they are embedded in larger systems (Bakshi & Fiksel 2003).

2.4 Specific aspects of the use of wood resources

Three areas that are raised in literature as major issues concerning the sustainability of the use of wood resources, and that have also been highlighted by the companies in the projects are biodiversity, impacts of land use and occupied land area.

The difficulties in finding practical ways to measure such a complex concept as biodiversity have led to approaches for measuring species richness, which is the number of certain species represented in a monitored area, e.g., the number of vascular plant species found in an inventory plot. This is applied although species richness does not capture much of the essence of biodiversity. In fact, numerous studies show that there is no correlation between species richness in one taxonomic group and species richness in other groups (Bonn & Gaston 2005, Grenyer et al. 2006, Orme et al. 2005). Biodiversity is a concept with a wide content. The Convention on Biological Diversity states that:

> *"Biological diversity" means the variability among living organisms from all sources including, inter alia, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part: this includes diversity within species, between species and of ecosystems. (UNEP 1992)*

How to measure biodiversity, or which species to protect and why, is not agreed on and seldom discussed. Furthermore, no one knows the exact rate at which species become extinct owing to actions by human beings. The estimates vary (MEA 2005), but all seem to agree that it is a matter of enormous proportions. And Rockström et al. highlights the rate of biodiversity loss as a planet boundary that humanity clearly and strongly has transgressed (Rockström et al. 2009). For most people, this is a depressing insight and many people seem to agree that to knowingly cause or significantly contribute to the extinction of entire species is bad and even morally wrong (Persson 2008). Therefore, it is rational to rule in favour of preservation also when the value of the species is uncertain. One appropriate way to act to preserve biodiversity and avoid the extinction of species is to prevent eliminating habitats (Sala et al. 2000). For forests, this would result in more area set aside for the protection of biodiversity. In this research project, compliance to forest certifications such as FSC (Forest Stewardship Council) and PEFC (Programme for the Endorsement of Forest Certification) could possibly be feasible as an acceptable level of responsible biodiversity protection, or at least a feasible way to manage this responsibility in the product sustainability assessment.

Direct land-use change, for example the conversion of non-agricultural land to agricultural land, as a consequence of increased production of agricultural products, will typically decrease the carbon storage capacity of the soil. If the biological feedstock is instead produced on degraded soil, with low original carbon storage capacity, it can potentially contribute to an improvement of the soil carbon storage capacity. Indirect land-use change refers to land-use change induced in other areas. For example, if agricultural land is displaced for forestry and triggers the agriculture to move to pastureland, then the indirect land use change refers to the sustainability impact of agriculture on the pastureland. This research project involves only Nordic forest area. If the demand for wood resources for fibre would increases as a result of the considered product, then the share of wood going to fibre production, or the wood harvesting, must also increase, which may lead to direct and indirect land use change.

Land use should not be mixed up with the occupation of the limited resource land area, sometimes referred to as land area occupation. An estimation of land area needed for adult incontinence products for the ageing population in Europe is presented in Chapter 4. It highlights the increasing competition for wood resources.

2.5 Product development stages

Product development starts with an idea and, if successful, ends with a product on the market. An illustration of different development stages that can be discerned for products is presented in Table 1. In the early phases of product development (the left-hand side of the table), it is not known for example which resources or materials will be used, the amount needed, where and how the materials and products will be produced or the potential production volume. The degree of uncertainty in terms of product system and the size of the market is high. In sustainability assessment, this provides a challenge since many of the details needed for a thorough sustainability evaluation are not available. At the same time, this provides an important opportunity to influence the process towards a more sustainable final product before all these potentially important choices have been made. Towards the right-hand side, more is known about the product system and there are fewer degrees of freedom for product development. Towards the left-hand side, the need for and the usefulness of a more future-oriented approach as a guide through sustainability considerations towards a vision of sustainability increases.

Table 1. Overview of product development stages

Product development stage	**Early development**	**Development**	**Demonstration**	**Production**	**Upgrade**
Situation	A first idea of a new material or product concept exists	Product concept exists but details are not set	Material or product is available in small quantities	Material or product is available on the market, the production process is known	Material or product needs to be renewed
Task	To develop idea and concept	To develop towards defined properties	To scale-up production processes	To optimize production processes	To improve material or product for example by optimisation or replacement of part or process
Time frame	Several decades / long-term	Years to decade / medium-term	Months to years / short-term	Months to years / short-term	Months to years / short-term

How to integrate sustainability concerns into several different stages of product development has been studied and reported in doctoral theses by Lundqvist (Lundqvist 2000) and Hallstedt (Hallstedt 2008). Both identify the visualization of a sustainable society, the future playing field for the product, as a key feature in any framework or approach to strategic actions for sustainable development. Thus, an approach that guides product development projects should include ways of creating visions of future sustainable societies.

2.6 Efforts to integrate sustainability considerations into product development

As discussed by for example Charter and Chick in 1997, environmental problems caused by industry have traditionally been addressed by end-of-pipe or repair strategies that minimize environmental impacts. In the long run, this often turns out to be costly and inefficient because it does not provide solutions to the problem from a systems perspective (Waage 2007).

A number of concepts and tools, like Ecodesign, Cleaner Production and Life Cycle Assessment (LCA) have been developed to make it possible to integrate environmental or sustainability aspects into different stages of product development (Karlsson & Luttropp 2006). These are generally constructed in such a way that they may result in the environmental improvement of existing products and consequently they focus primarily on the optimisation of the current product system, e.g., on replacing parts or processes representing large environmental impacts based on the industrial processes currently in use. Such approaches normally result only in marginal improvements compared to the present situation and cannot fully take advantage of truly innovative ideas that are based on completely different solutions. Since a more sustainable future society might put very different demands on products compared to the strictest environmental requirements of today, sustainable product development must be future-oriented, i.e., based on a vision of long-term sustainability and on an understanding of what challenges this poses to the product system that is being developed. This difference in focus, on either optimisation or future-orientation, has been discussed by Van Weenen in relation to sustainable product development (Van Weenen 1997). He argues that future-orientation requires that the project team has both a holistic perspective and a life cycle perspective in their considerations.

Tools or frameworks that have been created to provide guidance, informed by more long-term considerations, include the twelve principles of green chemistry developed by Paul Anastas and John Warner (Anastas & Warner

1998), which are particularly relevant in planning synthesis routes for chemicals, typically part of the early development or the development stage in Table 1.

Several approaches are based on applying the four principles for sustainability developed by Robèrt and Holmberg (Holmberg 1998) in four steps in a backcasting procedure in strategic planning towards sustainability (Holmberg & Robèrt 2000):

A. Defining criteria for sustainability
B. Describing the current situation in relation to the criteria for sustainability
C. Envisaging and discussing the future
D. Finding strategies for sustainability

One such approach aims to develop and test the robustness of a business idea (Lundqvist et al. 2006), but its use in a product development team has not been described. Another approach has taken this step further and has developed guiding questions to promote a holistic perspective in product development (Byggeth et al. 2007). As a complement to the guiding questions, and to provide an overview of major sustainability challenges and opportunities early on for the management and the product development team, templates for sustainable product development have been proposed (Ny et al. 2008). It can be argued that both of these approaches will always require a facilitator to develop and/or choose the guiding questions since the background is not known or understood by the product development team members themselves. Consequently, the desired understanding needed for the material or product developers to continue making informed decisions for more sustainable products can probably not be achieved.

Assessments are used to compare different product systems mainly in the development, demonstration and production stages of product development as they are described in Table 1. In assessments reported in literature, lists of predetermined parameters often seem to be used without critical reflection on their relevance in light of the specific situation (Bossel 2001, Niemeijer & de Groot 2008), see Paper I. How and why certain sets of parameters are selected is normally not described; they are often just referred to as the 'selected' or 'chosen' parameters, indicators or impact categories without providing the basis for how the parameters together respond to the specific challenges. Selections from premade lists can be useful provided that all relevant areas are covered. In companies, simple tools listing "unsustainable" versus "sustainable" materials, products and activities are often requested or even labelling systems that guide in material choices. However, the advice provided by such lists and labelling systems depends on the underlying description of sustainability. An environmental label is not a guarantee for a more environmentally sustainable material or product than one without a label since the labelling systems often only consider a few requirements and do not have a holistic perspective. Furthermore, these requirements are mainly based on current issues and might not point in a direction that is sustainable in the long term (Bratt et al. 2011, Rex & Baumann 2007). It has even been argued that present eco-labelling criteria might create barriers to sustainable innovation (Bratt et al. 2011).

Products give rise to sustainability impacts not only when the product is produced in the factory, but all the way from raw material extraction, via material production and product manufacturing, to use and waste management. To be able to make sustainability improvements and not only shift the burden from one life cycle stage to another, products should be considered in a 'life cycle perspective' (Rebitzer et al. 2004). Thus, the new wood-based absorbing material that is developed within a material development project will not only affect resource acquisition and material production, but also the manufacture of the product and potentially also the use of the product and its waste management options. An overview of the life cycle stages included in the sustainability assessment in this material development project is given in Figure 3.

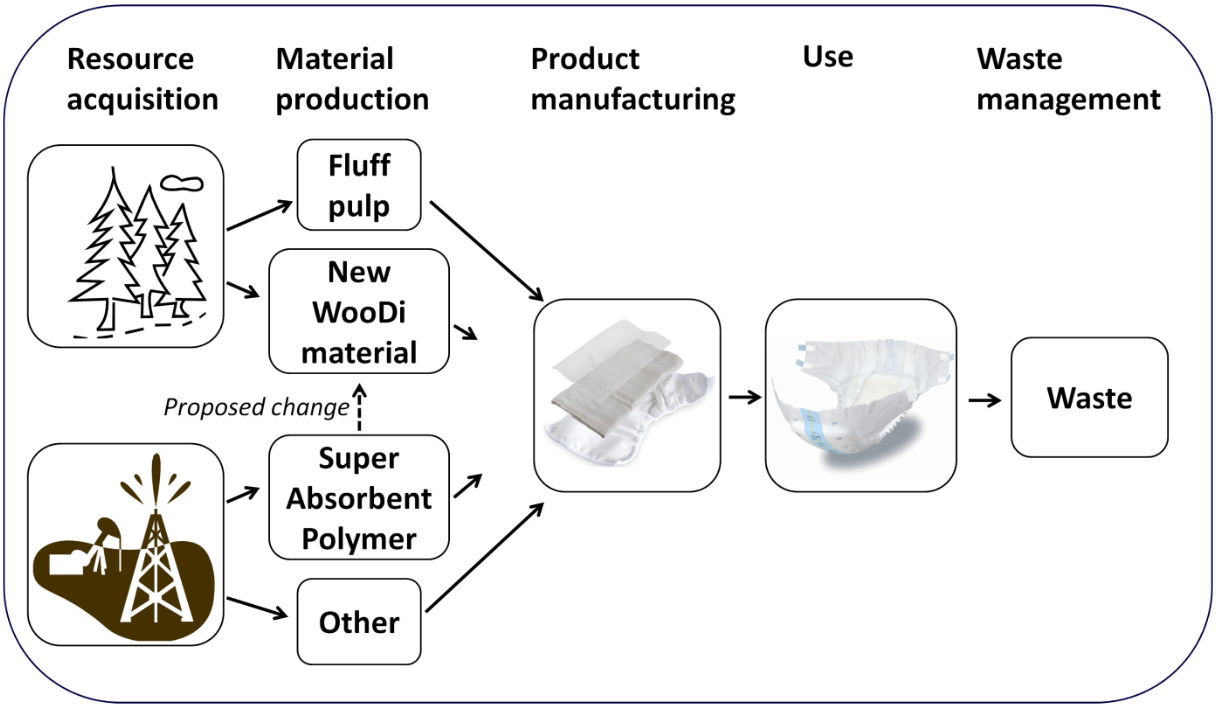

Figure 3. *Overview of the life cycle stages included in the sustainability assessment of the adult incontinence product. The material development project aims at developing new wood-based materials that can replace some of the petroleum-based materials in the product. A version of this figure is part of the conference contributions A and B.*

Furthermore, the whole life cycle of products needs to be envisaged in order to allow for relevant descriptions of sustainability. A description of a 'sustainable product' must be made in relation to the challenges that become visible when looking at a whole product system in relation to its surrounding world, which, to complicate this further, also changes over time, therefore requiring the application of an appropriate time perspective. From this, it follows that it is unwise to talk about 'sustainable materials' since the sustainability of the materials will depend on the full life cycle of the products in which they are eventually employed. Thus, the materials need to be put in a context.

Several authors point out that integrating sustainability thinking (when individuals reflect upon the sustainability impact of a product or activity in a long-term, holistic and life cycle perspective) is not a matter of developing more methods and tools or collecting more data, but rather an organisational problem (Baumann et al. 2002, BSI 2004, CALCAS 2008, Charter & Clark 2008). Therefore, case studies, applying existing knowledge, methods and data in real product development settings should be prioritised before additional technical solutions are developed in order to find barriers for implementation.

In addition, it takes time to integrate a sustainability approach at, e.g., a company as a new way of thinking and thereby working, and it can be useful to view the integration process as a learning process for employees. This was the general observation from a project for strategic planning towards sustainability at three multinational Swedish companies (Alänge et al. 2007).

How to prepare an organization to work with sustainable development was explored by Hardi and Zdan in 1997. They compiled the ten so-called Bellagio principles from a review of practical efforts of measuring, monitoring and assessing progress towards sustainability. The principles are general guidelines for an assessment process, for example, choosing adequate scope by adopting a holistic and long-term perspective when choosing and designing assessment parameters. They emphasize that necessary elements for successful sustainable innovation are: a guiding vision and goals, a holistic perspective, broad participation, and continuous assessment. The International Standard on *Integrating environmental aspects into product design and development* also gives guidelines on what to consider in a product development process and points out that product development is an iterative process in which information exchange, dialogue and collaboration are important features (ISO 14062 2002). Neither of these two documents, however, provides any guidance to how to establish relevant product sustainability assessment parameters in practice in a specific case of product development.

As a result of regulations that push for extended producer responsibility and of customers' increasing awareness of sustainability issues, most companies use one or several systems for monitoring and influencing sustainability impacts in different parts of their value chains, that is, when the product is on the market (the Production stage in Table 1). Examples of such systems are Environmental Management Systems (EMS) like ISO 14001; Corporate Social Responsibility (CSR) like ISO 26000; green public procurement for including environmental criteria in purchasing; and environmental labelling for helping consumers make informed decisions. In all stages of product development, one should be aware of these systems; however, the systems mainly affect the later stages. In the case of this research project, the development of criteria in green public procurement of incontinence products could be interesting to follow and maybe even influence.

Environmental Impact Assessment (EIA) is a legal requirement for assessing impacts that proposed projects may have on the environment, and are applicable to the Demonstration stage in Table 1. The development team should be aware of the EIA and its requirements throughout the development process to avoid permit denials and possibly shorten process time. In relation to the research in this project, an EIA will likely be needed to get a permit for the production facility of new material.

2.7 Team learning for guiding in product development

In order for a product development team to be able to make informed decisions, it needs to be continuously informed about important sustainability considerations and the potential effects of choices made. The importance of team learning in guiding product development has been pointed out by several authors (Edmondson & Nembhard 2009, Hardi & Zdan 1997, ISO/TR 14062 2002). In this thesis summary team learning refers to the process of working collectively to achieve common objectives in a group by acquiring, sharing and combining knowledge through experience with one another, as discussed in an article regarding a model for effective team learning in organizations by Decuyper et al. in 2010.

The need for a team-learning approach was highlighted by results from field studies at two large enterprises in the Swedish forest product industry, both with more than ten years of experience with LCA work (Rex & Baumann 2006). The authors have concluded that the translation of life cycle thinking into practical everyday work in each team is necessary for using LCA to deliberately guide the development process. Many of the employees in the field studies, including those who understood the life cycle concept, failed to see any link between the life-cycle-thinking ambitions of the company and their own everyday work. Therefore, it is vital to explore and communicate how each individual can use life cycle thinking to improve the result of their work in relation to company targets, for example, by translating such considerations into assessment parameters that have practical meaning for each team member.

Important demands on the surrounding organization arise when the goal is to integrate sustainability considerations into the product development process (Charter & Clark 2008). Two key factors, identified by Charter and Clark in 2008, are acceptance of the goal by managers on all levels, and employees' motivation to learn and to change. The authors have emphasized the need to identify the organization's level of awareness and understanding of sustainability issues since these will determine the type of approaches, the training, and the communication that are needed. In a cooperation project with several different types of organizations and cultures, this identification and training will most likely require more time than when performed within a single company. The project on Sustainability Integrated Guidelines for

Management developed the SIGMA Guidelines in order to provide practical advice to organizations in making contributions to sustainable development (BSI 2004). The guidelines focus on how to cooperate across knowledge areas and organizational boundaries in order to utilize knowledge that exists in different parts of the organization. If there is no commitment from team members to participate, such efforts most probably will fail (Mullen & Copper 1994). One identified reason for weak commitment is that conventional project set-ups often tend to limit learning and prohibit a long-term perspective by focusing on predefined outcomes and working on delivering results for these expected outputs instead of reflecting on outcomes and stimulating learning (Bell & Morse 2004, Bell & Morse 2007). This creates a gap between the ambition of developing more sustainable products and the delivery practice of conventional projects. Bell and Morse (2007) described a conventional project as *"defined activities carried out by defined people with a defined end point in mind at a defined cost and over a defined period of time"* and a holistic project as the opposite.

Beer and Eisenstat (Beer & Eisenstat 2000) have found that there are often hidden communication barriers to overcome when implementing strategies and achieving learning and change within an organization. A lack of shared understanding of project goals and of terms used in the project, like renewable resource, waste and product sustainability, generally make projects inefficient and create unnecessary tension and frustration (Decuyper et al. 2010). Open, vertical communication is important for overcoming such barriers (Beer and Eisenstat, 2000). All levels in the organization need to be engaged in an open dialogue about the organization's vision in order to acquire a shared understanding.

For this research project, and for similar situations, literature points towards the importance of the project team accepting the goal and the working procedure, and the creation of motivation for the team members to participate in activities aimed at communication in order to facilitate learning. In order to facilitate action for more sustainable final products the sets of assessment parameters, developed from the case-specific description of sustainability, need to be translated into something that has a practical meaning for each team member in their everyday work. This is generally omitted today although the product development team members are the ones that largely affect the sustainability performance of the finished product.

3. TEAM-LEARNING PROCESS FOR GUIDING PRODUCT DEVELOPMENT TOWARDS A MORE SUSTAINABLE PRODUCT

3.1 Points of departure

The suggested process builds on three fundamental points of departure that are sometimes implicit in projects that aim at assessing product sustainability in early product development but that are seldom clearly stated and, therefore, often forgotten. The importance of making these explicit and integrating them into the approach became clear after the initial literature studies and after beginning to test different elements in the project. These three points of departure are presented here.

Case specificity

Sustainability is a concept that can only be universally defined on an overarching level and, thus, it needs to be interpreted and described for each specific case or product. Sustainability depends on the management of materials or products during their entire life cycles rather than on certain characteristics of materials or products (Ny et al. 2006). The set of product sustainability assessment parameters that is relevant to use will differ, for example, with geographical locations and cultural contexts, over time and among product types. Different sustainability parameters might thus be more or less urgent or relevant for different systems (Marsden et al. 2010). Water, for example, might be an important input to a production process, however, its importance, in terms of availability, purity and price, varies in different parts of the world and will also potentially change with season and over time. Any sustainability assessment therefore has to be case-specific in order to address the specifics of the life cycles that are to be improved or compared in relation to their specific surroundings.

Future orientation

An important feature of any product is that it has the potential to fit into a sustainable society, or at least be a bridging solution that can assist in a move in that direction. However, what is perceived or experienced as the most critical parameters for sustainability might be very different in the future, compared to today. Thus, the envisioning of different potential futures is needed to guide the development of products. Presently, product assessments are most often based on the current situation, for example, on today's energy mix of fossil fuel, renewable power and nuclear power. Therefore, they do not take the future development of surrounding systems into account.

Technical system under development

In early phases of product development, it is not yet known, for instance, what resources or materials will be used, how much material will be needed, where and how the materials and products will be produced, how many products will be produced and how the wastes and products can be disposed of after use. Consequently, data for the product system is not yet available. Many available assessment tools can, therefore, not be applied to their full potential in early development stages since they are designed for assessment of existing products and are based on quantitative data for real processes. That so much remains unknown is a challenge but also an excellent opportunity to influence the process towards a more sustainable product.

3.2 Suggested process

In order to guide product development towards more sustainable products, approaches are needed that will facilitate (1) identifying significant aspects of sustainability by visualising the product in potential future sustainable societies, (2) describing these aspects as a set of assessment parameters, (3) translating this set so that it provides meaning to the different team members in their specific areas of work, and (4) providing a holistic understanding of the sustainability performance by involving the whole team in the valuation and interpretation of the relative importance of different impacts. Knowledge about the product system, about relevant assessment parameters and the sustainability performance of the product system can be enhanced over time in an iterative procedure, as described and illustrated in Paper II. The paper describes a methodology that is at first based on an assumed product system together with a case specific and future oriented interpretation of essential sustainability considerations for the product system, applying a participatory approach. Figures 4-6, below, represent the three steps of the process.

An essential element in the process is to explicitly describe what sustainability implies in each specific case, namely, what to include in the concern and how to handle trade-offs and uncertainties like insufficient data, as described in Chapter 2.1. This is handled in the first step of 'defining long-term goal and determining scope' in the suggested process for guiding the material or product development towards a more sustainable product by team learning, illustrated in Figure 4. This part is only briefly described in Paper II; some examples of exercises carried out in the project to achieve this are described in Chapter 4.1.

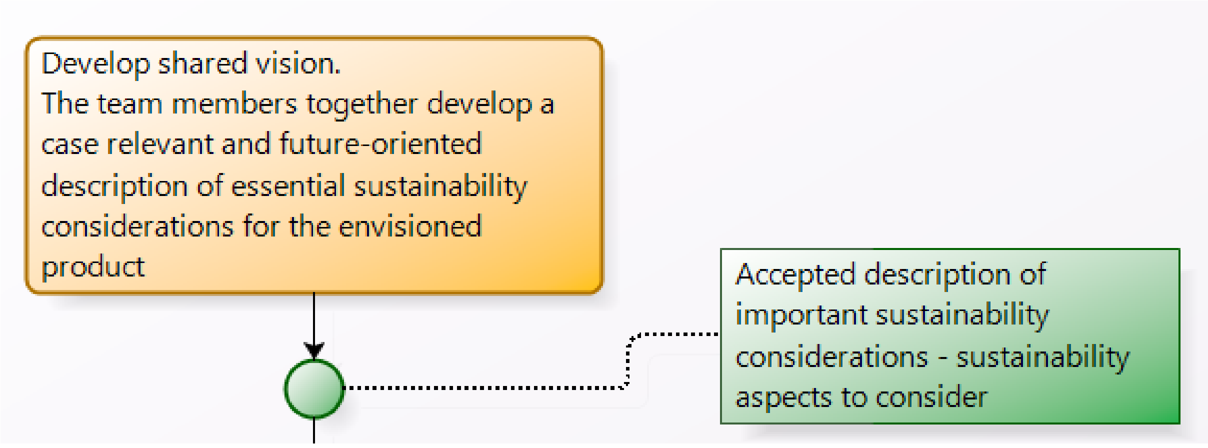

Figure 4. *The first step of 'defining long-term goal and determining scope' in the suggested process for guiding the material or product development towards a more sustainable product through team learning.*

In order to compare and improve the sustainability of a product, it is necessary to increase the project team's understanding of important sustainability considerations during early stages of development. To accomplish this, the project team members need to be involved in a process that is based on their knowledge and experience and that adds to this an understanding of potential sustainability consequences. In the suggested process, this is done by first identifying relevant sustainability assessment parameters and then translating them into parameters that are relevant for each project team member's specific area of work. Provided with this and with the description of what sustainability implies in the specific case makes it possible for the team to generate more sustainable ideas. In this process, all team members will, at some stage, need to utilise or relate to the product sustainability parameters and results from recurring assessments of the sustainability performance of the product in their work as guidance to and inspiration for how they can influence the sustainability of the product. The second step of 'establishing sets of product sustainability assessment parameters' in the suggested process is aimed at facilitating this. This step is illustrated in Figure 5.

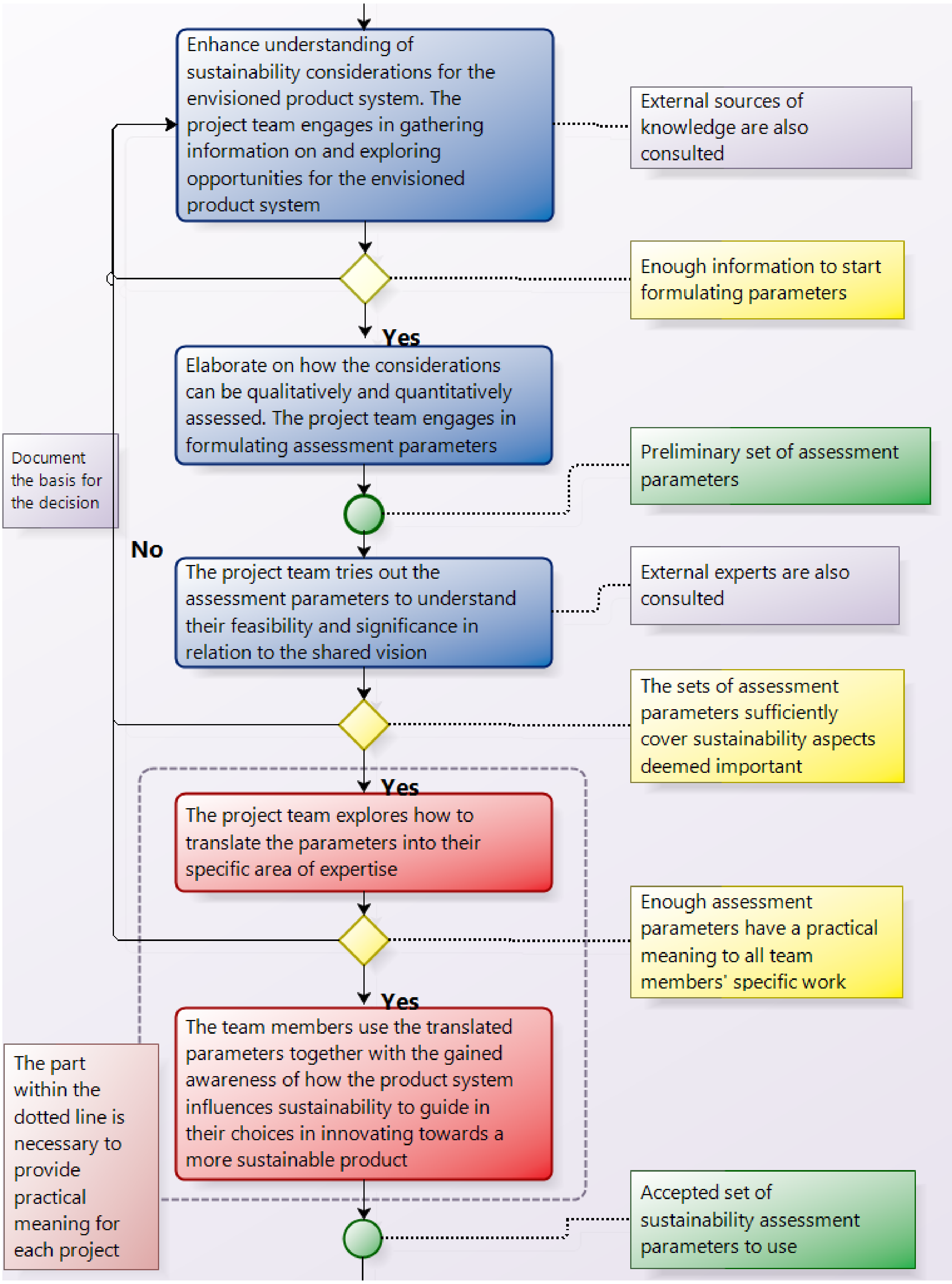

Figure 5. *The second step of 'establishing sets of product sustainability assessment parameters' in the suggested process for guiding the material or product development towards a more sustainable product by team learning.*

In the final step, assessing holistic product sustainability, a holistic understanding of the sustainability performance is provided by involving the whole team in the valuation and interpretation process. The process involves discussions on the contribution of each product's life cycle to societal problems, and decisions on the relative importance of different impacts. The step is illustrated in Figure 6.

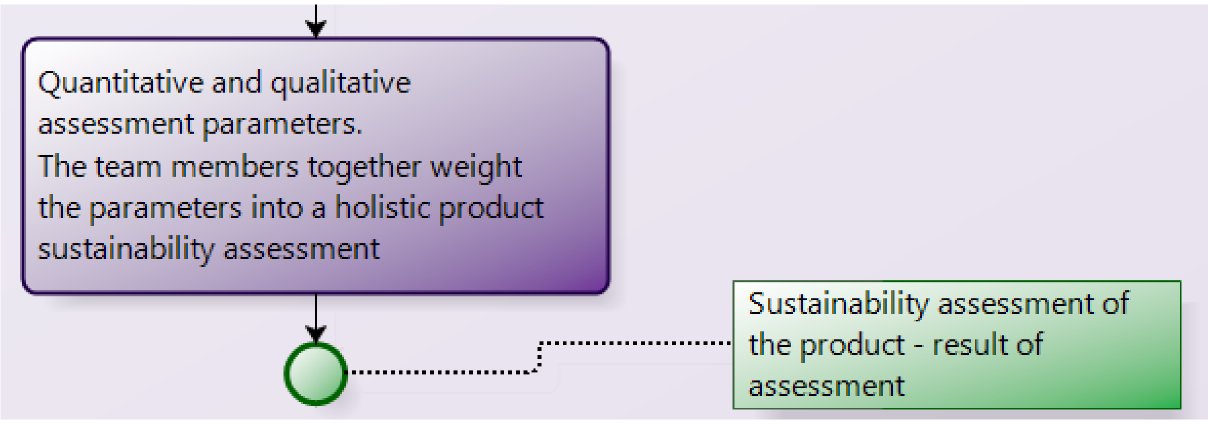

Figure 6. *The third step of 'assessing holistic product sustainability' in the suggested process for guiding the material or product development towards a more sustainable product by team learning.*

The suggested process will not be further discussed here, since details are available in the appended Paper II. Instead, descriptions and evaluations of some activities that were carried out in the project to accomplish the three different steps of the process will follow. The activities are also described in brief in Paper II. The results of evaluations of the activities when performed in the project have provided important input to the development of the process that is presented in Paper II and in this thesis summary.

4. EXPERIENCES FROM APPLYING ELEMENTS OF THE TEAM LEARNING PROCESS

The team-learning process suggested in Paper II is a way to guide product or material development towards more sustainable products. The process was developed based on understanding obtained partly from literature studies, and partly from conclusions of analysed experiences in the project. This section provides details on the practical efforts. In 4.1-4.3, different exercises are described and in 4.4, some common issues in this type of research and development projects are highlighted.

4.1 Defining long-term goal and determining scope

Early on in the project, the material development team was busy starting up the research work on the development of the new wood-based superabsorbent materials. The steering group of the project and contact persons at the companies were, therefore, asked to engage in developing a description of what the qualities of a 'more sustainable product' should be in the project. The plan was to deliver a list of relevant product sustainability aspects and visualisations of potential future societies to the material development team. At a first workshop, the four principles of sustainability listed in Chapter 2.1 and the backcasting methodology were introduced. Examples of what 'sustainable development' could imply were presented in order to demonstrate that 'sustainable development' is not a clearly defined concept. To clarify the different views of sustainability among group members, a discussion of what a sustainable society comprises that could influence material and products was held and documented as a mind map. The content in the mind map was then contrasted with the four principles of sustainability in order to verify that these were covered. Present state analysis of how each company today influences the sustainability of a product was also made. The analysis aimed at defining what activities, throughout the product's entire life cycle, are unsustainable and which roles in the company can influence the activities and how. At a second workshop with this group, the principles of brainstorming were presented and a brainstorming activity was performed in order to identify various potential solutions for the product in a sustainable future. Further workshops could have been carried out with this group, but due to other priorities, workshops were instead continued with the material development team, which provided the advantage of working with the people that influence the detailed development of the project in terms of material development in their every-day choices.

To increase the material development team's understanding of how developments in the world can affect the sustainability of a product, a scenario analysis was performed, following the description by Lundqvist et al. (Lundqvist et al. 2006). First, external factors, for example, those concerning customers, politics, environment, competitors, economy, society, suppliers and technology, which may influence the final product, were identified in a brainstorming activity. Examples of factors that were discussed are: increased costs for transportation, patents that cease to exist, and greater considerations of global equity. The identified factors were discussed and placed in a diagram based on their predictability and on their potential impact on the sustainability of the final product. Only the factors that may have a high impact were considered in the selection of factors for the development of scenarios of the future. Factors with a relatively high predictability were classified as *trends* and factors with a relatively low predictability were classified as *critical uncertainties*. Based on two unrelated critical uncertainties, four different future scenarios were generated, as illustrated in Figure 7. The four different future scenarios were intended to be used to test the feasibility and robustness of different suggested technical solutions.

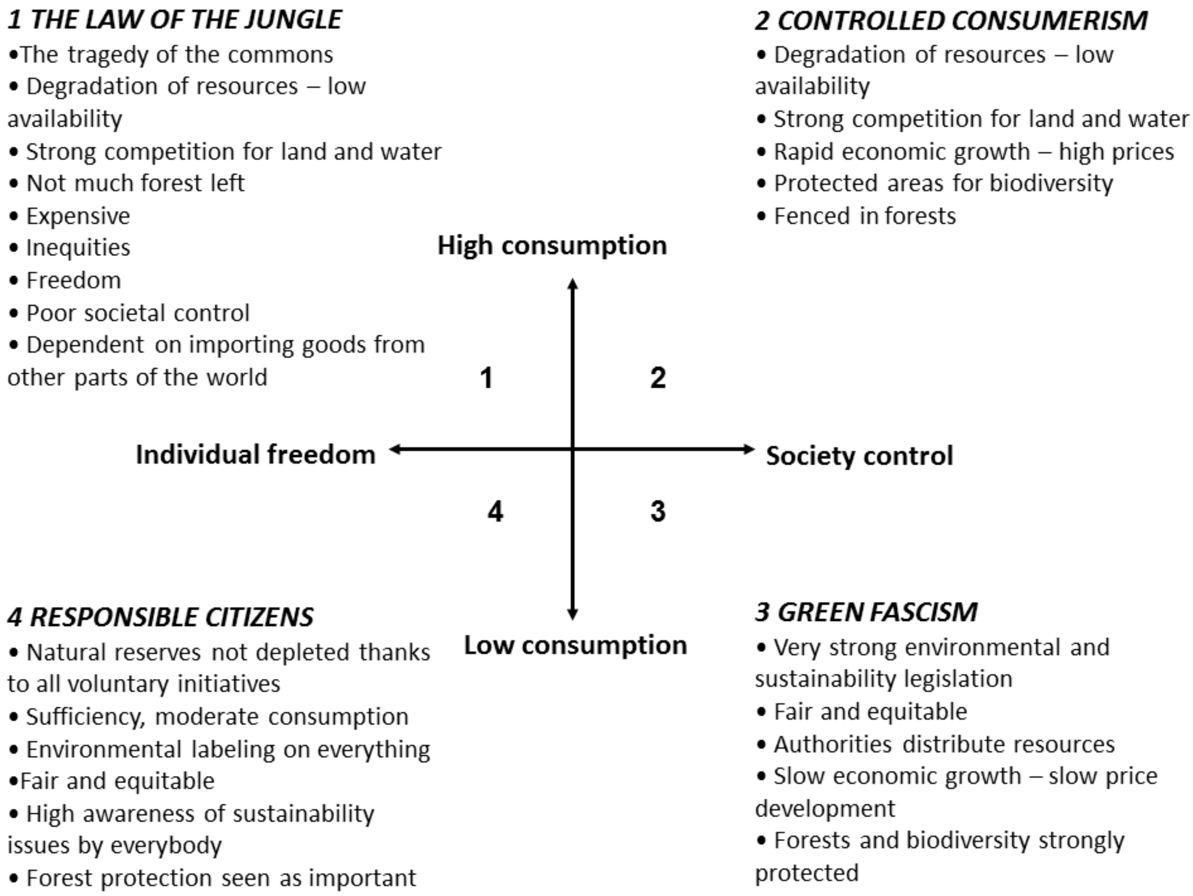

Figure 7. *Results of the scenario analysis. The two selected unrelated 'critical uncertainties' form the two axes and four scenarios are generated in the quadrants. All 'trends' are also considered in each of the scenarios.*

To enhance the understanding of potential long-term effects of increased wood resource use, various estimates were presented early on in the project. For example, an estimate of the forest area required for adult incontinence products in Europe until 2050 was presented and is attached in Appendix A. The calculations show that the forest area needed for severe incontinence products in Europe will increase by about 75% until 2050, using current projections of population growth and assuming the same fraction of population with severe incontinence, the use of disposable incontinence products, and the same yield from Swedish forestry as of today. The area needed in 2050, under these conditions, corresponds to an increase of 75% from 2010 to 1.2 million hectares forest area, which is a small share of the Swedish forest area, 5.3%. However, such an increase in wood demand for only one product is not without problems, since forests, to a large extent, are already utilized, e.g., for timber, and pulp and paper production. Since there is an expected increase in demand for bio-based fuels and materials to replace petroleum-based products, this factor means competing for either the yield from the forests or for the land area (Beland-Lindahl & Westholm 2011). At the same time, there are rising concerns regarding biodiversity and other ecosystem services as discussed in Chapter 2. Consequently, there was a need for the project to discuss how to handle this trade-off. A discussion started on how an increase in the extraction of wood should be viewed. Is there a linear relationship between increased fibre extraction and increased forest area or will this be handled by a redistribution of wood directed to, e.g., sawn timber products, fibres and combustion?

4.2 Establishing sets of product sustainability assessment parameters

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 kind of equipment will be used and many other things. Therefore, a scaled-up model of a conceptual production process, developed from lab scale data, is sometimes used for generating estimates of input parameters for an LCA study. Resistance to the use of preliminary process estimates for environmental assessments may be encountered from the developers when the material design has not yet progressed past the bench-test scale. Results can be seen as threats to innovation if they are unfavourable. Nevertheless, such preliminary calculations are important in the development of more sustainable products since they may highlight particular challenges. It is important to use these early LCA results exclusively as indications based on coarse assumptions and not to be lured into seeing them as the last word on the product's environmental performance.

Results and conclusions of early LCA estimates were used in the project to enhance the understanding of the adult incontinence product system and the challenges to different environmental parameters involved in replacing petroleum-based material with wood-based. These estimates showed that unless there are positive impacts in other areas that can compensate, the environmental impacts from the production of the new material cannot be allowed to be higher than from Nordic fluff pulp production if the new material is to be more environmentally benign than the reference for the most common environmental parameters. In particular, performance in terms of energy demand for the new material proved to be a challenge. Consequently, developing materials to replace available optimised materials, while at the same time ensuring a more sustainable product, is a challenge. It requires not only a shift to renewable resources or an environmental optimisation of material production processes but also considerations of relevant sustainability aspects throughout the entire life cycle of the product while retaining or even improving product function. This demands the material development team's awareness of important sustainability considerations. For more details on the LCA estimates, see Paper III.

An exercise aimed at creating greater and shared understanding of the aspects and assessment parameters was carried out with the material development team. The team was divided into three groups and each group received six different sustainability aspects that had been selected by the sustainability assessor in order to cover a broad range of sustainability aspects that may be important during the adult incontinence product's life cycle. The sustainability aspects' importance for the project was discussed in each group. Assessment parameters describing the aspects were proposed by the three groups and further discussed. This gave the material development team an opportunity to learn and also to influence the basis for the sustainability assessment of the final product. For examples of considered aspects and parameters, see Paper II.

A material checklist template containing sustainability considerations for new materials was developed for the project, as demonstrated in Figure 8. It was aimed at facilitating a first rough sustainability assessment, together with the material developers, of the new materials that were to be produced within the project and making material developers aware of the sustainability challenges and opportunities of new materials at a very early stage. When the material checklist was used, it was revealed that most sustainability considerations, for example the use of chemicals use and the share of certified wood, lack direct significance to the material developers in their work, and may instead be more relevant parameters for the process technicians and purchasers that work with efficiency improvements and the company's purchasing strategy. The difficulty in providing information to the material developers that is meaningful to them in the sense that it gives advice on how they can change their actions to influence sustainability was revealed, however, the checklist still gave them an awareness of and insight into a broader sustainability perspective.

Material checklist				
Name of material:				
Chemicals used:				
Tree spieces:				
Wood fibre source:				
Main function of material:				
Date:				
Participants:				

	Yes	No	Comments
Is the wood certified?			
Is recycled wood fibre used?			
Is it reuse of fibre?			
Is the REACh status of the chemicals checked?			
Does the chemicals fulfill Company A demands?			
Does the chemicals fulfill Company B demands?			
Is all energy use in material production and diaper manuafacturing renewable?			
Result	0		

Compared to reference diaper	Increase	Equal	Decrease	Comments
Energy use				
Wood use				
Petroleum oil use				
Water use				
Chemical use				
Risk for safety and health injuries				
Result	0			

Figure 8. *The template for the material checklist that was developed for the material development project.*

When developing a material that is intended to replace another, it is important to understand which specific material properties are needed in order to deliver the desired function. It would be counterproductive to copy all 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 sustainability performance in different life cycle stages of the product.

A workshop was, therefore, performed with the material development team, with the aim of finding the material parameters that connect the strongest to the product function. The workshop focused on describing customer needs for the adult incontinence product and connecting these needs to material properties that the material development team work with in their daily activities. This gave more clarity about the properties to be improved and why.

4.3 Assessing holistic product sustainability

In the beginning of the material development project, a multi-criteria analysis exercise was carried out with the project team, in order to provide an understanding of the general principles of the sustainability assessment at an early stage, and the issues that may arise. The groups formulated sustainability aspects that they expected would have a large effect on the adult incontinence product's sustainability performance. The envisioned new product and the reference product were both graded from one to five after how well they were expected to perform for each aspect (five indicated very good performance). The aspects were also given weighting factors from zero to two depending on their perceived relative importance. The grade and the weighting factor were multiplied for each aspect and the results were added together for each alternative and compared, as illustrated in Table 2. This gave the team an insight into how an assessment may be performed, what can be included in the assessment and what the uncertainties and difficulties are.

Table 2. *The result of one multi-criteria analysis performed early on in the material development team.*

	Aspect CO_2 **Factor** 1.5	**Aspect** € **Factor** 1	**Aspect** Function **Factor** 2	**Aspect** Waste **Factor** 1.3	**Aspect** Resources **Factor** 1.8	**Aspect** Social **Factor** 0.7	**Sum**
Reference product	2 x 1.5 = 3	3 x 1 = 3	4 x 2 = 8	3 x 1.3 = 3.9	2 x 1.8 = 3.6	4 x 0.7 = 2.8	24.3
New product	4 x 1.5 = 6	2 x 1 = 2	4 x 2 = 8	4 x 1.3 = 5.2	4 x 1.8 = 7.2	4 x 0.7 = 2.8	31.2

Before all potentially important aspects and parameters have been identified and assessed, it may be important to visualise the overall performance of the new product compared to the reference product. In the project, sustainability profiles were used to illustrate this. These were updated regularly as more knowledge about the adult incontinence product system, relevant assessment parameters and the resulting sustainability performance emerged. The sustainability profile, as used in the project, compares sustainability aspects of the new product to a reference product as illustrated in Figure 9. The x-axis in Figure 9 shows some parameters that were identified as important at the time and the y-axis shows the relative performance in relation to the worst performing alternative for the parameters that had been quantified at that time. As seen in Figure 9, the new product did not, at the time, exhibit an improved performance for all aspects compared to the reference. The need for handling trade-offs in a structured and transparent way became clear to the project team.

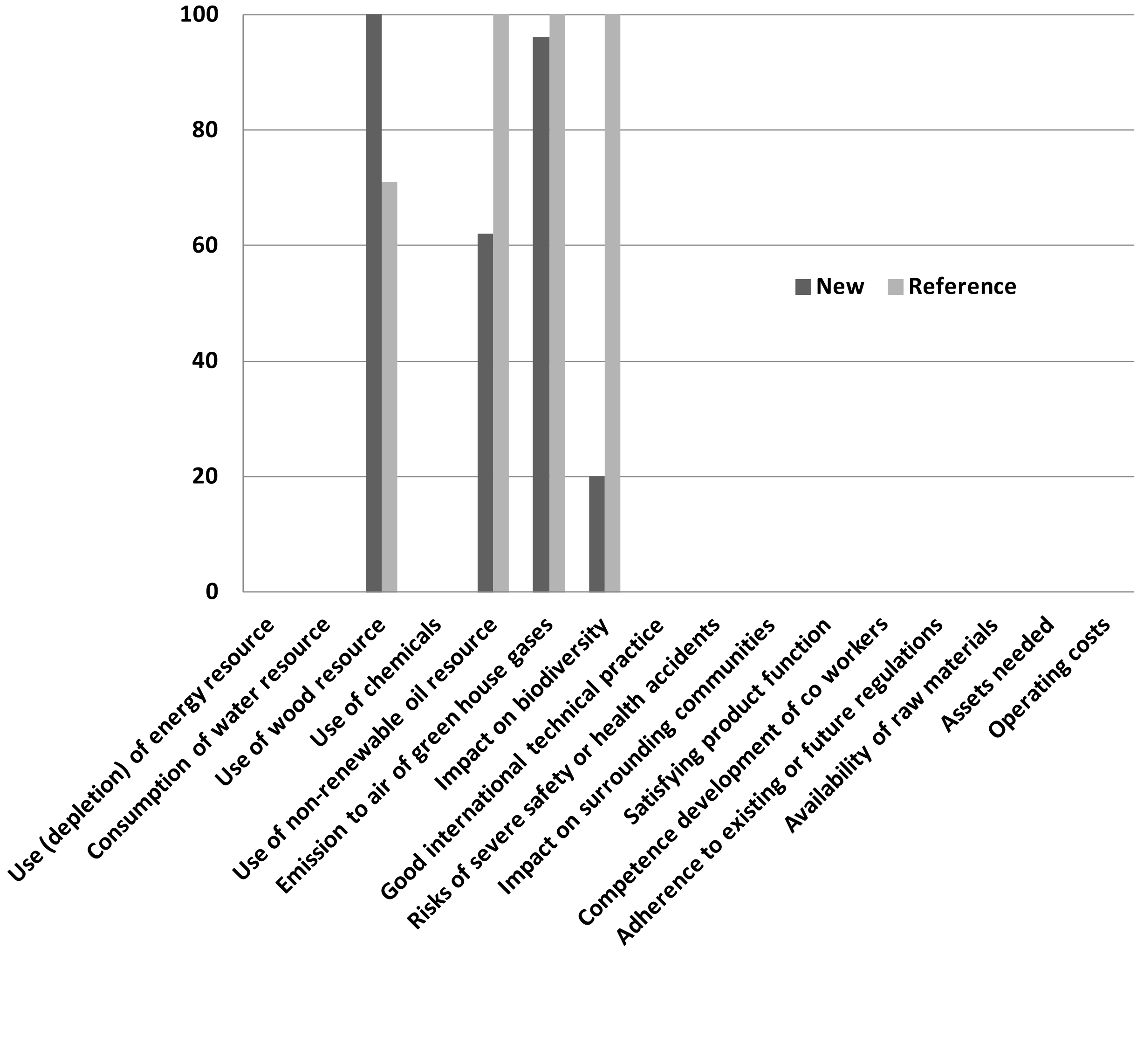

Figure 9. *Example of a 'sustainability profile' with selected sustainability parameters, comparing a potential new adult incontinence product with the reference used in the project, presented as percentage relative to the highest contributor.*

4.4 Common issues in research and development projects of materials and products

The exercises described in 4.1-4.3 were all done with the intention of eventually resulting in a product that performs better than the reference. Since all of the exercises were performed before the final assessment framework had been finalized, they all aimed at both providing input to the forming of the assessment framework and providing guidance to the team on how to maximize the sustainability performance. The suggested process described in Paper II and 3.2 was put together as a result of literature studies and after analysing different exercises that had been tried out in the project. There are many reflections to make concerning these efforts and parallel projects described in literature. Here, some generic issues, applicable to many research and development projects of this type, are briefly discussed.

Although a lot of effort must be put into presenting the background to why and how different workshops are carried out, as well as the potential gain of participating, participants can end up in expecting something else than the activities at the workshops and their outcomes. One reason for this might be that different project members have a different pre-understanding of what a sustainability assessment should comprise and how it should be performed. Also, project members may not be convinced about the importance of them learning about how they can influence development. The great importance of preparing and motivating the participants in an appropriate way for their time and attention during activities is clear.

Scenarios and strategies is something that the management level of a company often works with, but more rarely a team like a material development team. In this project, workshop participants on management level, not surprisingly, showed the greatest interest among the participants for analyses of future scenarios. However, once the rest of the group started to discuss the scenarios, they could all contribute very positively to the discussion.

In projects of this type, it could be useful to identify challenges to integrating learning and achieving change by finding out more about the participants' different needs, their attitudes towards the project and their power to act, at an early phase in the project. One way to do this is by performing a stakeholder analysis (Bell & Morse 2008).

5. CONCLUSIONS

Most available sustainability assessment tools are not applicable in early development stages since they are aimed at assessing existing products and are based on quantitative data for existing processes.

Tools for integrating environmental or sustainability aspects into different stages of product development are generally constructed in such a way that they only result in the environmental improvement of existing products, e.g., on replacing parts or processes representing major environmental impacts based on the industrial processes used today.

The set of sustainability assessment parameters that is relevant in relation to a specific product will differ for different cases and needs to be established for each specific situation.

Establishing relevant product sustainability assessment parameters is not a simple task. It needs to involve several actors in an iterative procedure.

Sustainability assessment parameters for comparing the use of non-renewable and renewable resources are largely lacking.

The developers strongly affect the sustainability performance of a finished product. To make it possible for them to rethink and move towards a more sustainable final product, developers need to know of *and* understand which surrounding world and future-oriented considerations that make significant impacts on a specific product's sustainability performance. It is not enough to provide developers with parameter results to improve, but they also need support in translating and integrating the parameters into something that can guide them in their area of expertise.

6. RECOMMENDATIONS FOR FURTHER RESEARCH

The analysis in Paper I identified a lack of product sustainability parameters on social progress and on impacts on ecosystem services, such as biodiversity, and on competition for different types of limited resources, like petroleum, land area and water. Consequently, research into this area is needed.

Case studies are needed to demonstrate practical experience of how relevant product sustainability assessment parameters can be established, for example, by applying the process suggested in Paper II and evaluating it and identifying its limits. To promote innovation towards more sustainable products, studies are needed on how to guide developers. In order to define the barriers and test how to overcome them, case studies should be conducted.

Project set-ups with predetermined deliverables may not be suited for some research and development projects since it may limit learning by preventing the utilisation of new knowledge and understanding gained in the project. Therefore, research is needed on how to set up this type of development projects in order to encourage a long-term perspective and learning.

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APPENDIX A

The ageing society – an example of consequences for biomass use

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Increasing life expectancy results in an ageing society in parts of the world. The old of tomorrow are also expected to have higher comfort demands (Wuagneux 2006). One likely consequence is an increase in the need of such products as disposable incontinence diapers, which are today partly based on cellulose from forestry. A calculation of the potential increase for severe incontinence care (assuming the use of disposable incontinence diapers) was made based on the demographic trends for Europe and on the yield from forestry performed under Nordic conditions. The calculation is shown here using a vector decomposition known from literature (Holmberg 1998): ***I = i * m * u * P***. It expresses the impact (I, in our case, forest area in ha) as a product of four factors that humans have the ability to change, in our case, i = ha Nordic forest area / kg material (Swedish forest agency 2009), m = kg material / service, u = service / population in Europe, and P = population in Europe (United Nations 2009). The 'service' is to keep a customer with severe incontinence dry for a year, assuming that the same fraction of the population above 50 years as today will need severe incontinence protection.

Under these assumptions, the forest area needed for severe incontinence care in Europe will increase with about 75% until 2050. If also the oil-based material in the diapers were to be replaced by wood-based, this would further increase the needed forest area to 136%, assuming a 1:1 replacement ratio by weight. This is still a small share of the total European forest area (0.2%). However, such an increase in wood demand for only one product is not without problems, since forests to a large extent are already utilized, e.g. for timber and pulp and paper production, and since there is an expected increase in demand for bio-based fuels and materials for replacement of petroleum-based products, thus competing for either the yield from the forests or for the land area. At the same time, there are rising concerns regarding biodiversity and other ecosystem services in connection to forestry (MEA 2005; TEEB 2009). Consequently, since forests area limited resource, there is a need for a discussion within society about how to dedicate forests.

Table 1. Estimation of forest area needed for disposable incontinence diapers for the ageing population in Europe.

Year	**2010**	**2020**	**2030**	**2040**	**2050**
P / population	732 759 000	732 952 000	723 373 000	708 489 000	691 048 000
u / (service / population)	0.011	0.013	0.015	0.020	0.021
m / (kg material / service)	84				
i / (ha forest area / kg material)	0,0010				
I / ha forest area = i * m * u * P	690 000	800 000	930 000	1 190 000	1 210 000

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APPENDIX B

	Sustainability aspect	Sustainability parameter	Reference discussing the sustainability parameter	Case study using the sustainability parameter
Environmental impact	**Use of energy resource**	• Energy use (renewable) • Energy use (non-renewable) • Energy use (electricity from the grid) • Consumption of energy	[1-3] [1-3] [1-3] [4-10]	[6-7, 10-13]
	Consumption of water resource	• Consumption of water	[2-10]	[6-7, 10-11, 13]
	Use of biomass resource	• Wood resource use • Consumption of biotic resources	[1, 6-10] [2-5]	[6-7, 10-11, 13]
	Use of chemicals	• Consumption of chemicals	[2-4]	
	Use (depletion) of non-renewable resource	• Consumption of abiotic resources	[2-10]	[6-7, 10-11, 13]
	Disposal of waste	• Solid waste • Dispose chemicals, containers, liquid and solid non-organic wastes including fuel and oil in an environmentally appropriate manner at off-site locations.	[2-10] [14]	[6-7, 10-11, 13]
	Emission to air of green house gases	• Calculation of GHG emissions via an lifecycle assessment • Improve climate change mitigation over time • Greenhouse gas emissions per process • Emissions to air • Net change in forest ecosystem carbon • Forest ecosystem carbon storage by forest type and age class • Available carbon credits in British Columbia's forest sector • Total forest products carbon pools and fluxes • Report separate subtotals for emissions of CO2, CH4, N2O, HFCs, PFCs, SF6 in tonnes and tonnes of CO2 • Forest sector carbon emissions • Use and emissions of ozone-depleting substances (in tonnes of chlorofluorocarbon-11 (CFC-11) equivalents) • Total forest ecosystem carbon pools and fluxes • Avoided fossil fuel carbon emissions by using forest biomass for energy	[5-10, 15-18] [15] [1] [2-4] [19] [19] [19] [19] [19] [19] [19] [19] [19]	[6-7, 10-13]
	Emission to air (apart of global warming gases)	• Emissions to air	[2-4, 6-10]	[6-7, 10-11, 13, 20]
	Emissions to water	• Maintain or enhance the quality of the surface and groundwater resources • Emissions to water	[15] [2-4, 6-10]	[6-7, 10-11, 13, 20]

	Sustainability aspect	Sustainability parameter	Reference discussing the sustainability parameter	Case study using the sustainability parameter
	Emissions to soil	• Identify and minimise air pollution emission sources • Eliminate open-air burning of residues, wastes or by-products. • Emissions to soil	[15] [15] [2-3]	
	Impact on forests, lands, wetlands, wildlife, habitat etc	• Respect water needs for the long-term sustainability of ecosystems • Withdraw surface or groundwater resources beyond replenishment capacities • Acidification • Euthrofication • Photo-oxidant formation • Recognise, maintain, and, where appropriate, enhance the value of forest services and resources such as watersheds and fisheries. • No occurrence of conversion to plantations or non-forest land uses, except in circumstances where conversion: a) entails a very limited portion of the forest management unit; and b) does not occur on high conservation value forest areas; and c) will enable clear, substantial, additional, secure, long term conservation benefits • Wild salmon and fish populations (Change in numbers of fish by life stage, by species, Habitat quality) • Strictly protected forest reserves • Forests protected by special management regime • Area of forest disturbed by fire, insects, disease, and timber harvest • Area of forest with impaired function due to ozone and acid rain • Area and type of natural disturbances • Area and type of human-induced disturbance • Human actions that could modify natural disturbance • Areas (ha.) identified with epidemic levels of forest health agents such as bark beetles, budworm etc • Changes in soil fertility, structure, and function in harvested areas • Landscape patterns • Connectivity between areas with similar habitat types (tree species, age class, etc.) • Percentage of area declared as mixed-species regeneration • Area and percent of forest affected by biotic processes and agents beyond reference conditions • Area and percentage of forest land with diminished or improved components indicative of changes in ecological processes • Area and percent of forest affected by abiotic agents (e.g., fire, storm, land clearance) beyond reference conditions • Scale and impact of changes in soil acidity in productive forests • biodiversity conservation	[15] [15] [2-3, 6-10] [2-3, 6-10] [2-3] [14] [14] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19]	[6-7, 10-11, 13, 20]
	Impacts from waste treatment (emissions, land	• Amount (km) of road where protective road measures are carried out to minimize soil erosion • Area and percentage of forest whose	[19]	

	Sustainability aspect	Sustainability parameter	Reference discussing the sustainability parameter	Case study using the sustainability parameter
	use, resource depletion)	designation or land management focus is the protection of soil or water resources • Protective function • Soil • Proportion of forest management activities that meet best management practices to protect soil resources • Proportion of forest management activities that meet best management practices to protect soil resources • Percentage of annual harvest area with soil loss due to establishment of permanent access roads • Area and percentage of rangeland with significant change in extent of bare ground • Area and percent of forest land with significant soil degradation • Area and percent of forest assessed for soil erosion hazard, and for which protection for soil and water values are implemented • The total quantity of organic carbon in the forest floor (greater than 25mm diameter components) and in the surface 30cm soil • Scale and impact of changes in soil acidity in productive forests • Proportion of forest management activities that meet best management practices to protect water-related resources • Disruption of aquatic habitat • Channel form within treatment area versus channel form upstream • Channel stability • Percentage of water bodies in forest areas with significant variance of biological diversity from the HRV • Proportion of watersheds with substantial, stand-replacing disturbance in the last 20 years • Peak flow index (includes Equivalent Clearcut Area calculation) • Percentage of stream km in forest catchments in which stream flow and timing has significantly deviated from the HRV • Percentage of stream km in forest catchments in which stream flow and timing has significantly deviated from the HRV • Significant discharges to water by type of effluent or waste (pulp mills, etc.) • Area and percentage of water bodies, or stream length, in areas with change in physical, chemical, or biological properties	[19] [5, 19] [6-9, 19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19]	
	Impact on biodiversity	• Identify and protect High Conservation Value areas, native buffer zones, ecological corridors and other public and private biological conservation areas • Protect, restore or create buffer zones • Protect, restore or create ecological corridors to minimise fragmentation of habitats • The toxicity potential • Human toxicological impacts • Area of forest, by type and age class, and wetlands in each ecozone • Habitat supply for indicator species	[14-15, 21] [14-15, 21] [14-15, 21] [4] [2-3] [19] [19]	[20, 22]

	Sustainability aspect	Sustainability parameter	Reference discussing the sustainability parameter	Case study using the sustainability parameter
		• Structural stage distribution by biogeoclimatic zone by site series over time	[19]	
		• Area of forest community types with significantly reduced area	[19]	
		• Area of forest, by type and age class, soil types, and geomorphological feature types in protected areas in each ecozone	[19]	
		• Area of forest by type, age class, and BEC zone in protected areas	[19]	
		• Range of sizes and average size of protected areas for each forest type	[19]	
		• Percentage of protected areas connected by biological corridors	[19]	
		• Outstanding or unique biological, zoological, geological, and paleontological features in protected areas	[19]	
		• Total forest cover in relation to area of forest outside of protected areas	[19]	
		• Area of forest under management in relation to area of forest in protected areas	[19]	
		• Area and percent of forest in protected areas by forest ecosystem type, and by age class or successional stage	[19]	
		• Area and percent of forest by forest ecosystem type, successional stage, age class, and forest ownership or tenure	[19] [19]	
		• Fragmentation of forests		
		• Percentage of non forest areas (e.g. wetlands, all terrain vehicle tracks, non productive brush) by landscape unit by licensee	[19] [19]	
		• Wildlife Tree Classes 1 and 2 (live trees), and 3+ (standing dead trees)	[19]	
		• Amount and type (size, species, and decay class) of course woody debris (cwd)	[19]	
		• Amount of windthrow	[19]	
		• Harvesting constraints and ecological attributes used to anchor retention	[19]	
		• Fragmentation of forests	[19]	
		• Number and status of native forest-associated species at risk, as determined by legislation or scientific assessment	[19]	
		• Change in the status of threatened and vulnerable species or indicator species	[19]	
		• Number of forest-dependent species classified as vulnerable, threatened or endangered within the forest management area (FMA)	[19] [19]	
		• Number, type, and severity of threats to species at risk (cumulative risk index)	[19]	
		• Percentage of original range occupied by selected rare, threatened, or endangered species	[19] [19]	
		• Areas of high-, medium-, and low-value habitat by species over time	[19]	
		• Population levels of selected forest-associated species	[19]	
		• Population growth rates	[19]	
		• Changes in the number and percentage of threatened species in relation to total number of forest species	[19] [19]	
		• Change in relative abundance	[19]	
		• Rate of change in community species assemblages over time	[19]	

	Sustainability aspect	Sustainability parameter	Reference discussing the sustainability parameter	Case study using the sustainability parameter
		• Populations of critical species	[19]	
		• Distribution of selected forest-associated species	[19]	
		• Number of forest-dependent species that occupy a small portion of their former range	[19]	
		• Percentage of area of mature forest within Landscape Unit and biogeoclimatic variants	[19] [19]	
		• Area of forest permanently converted to non-forest land use	[19]	
		• Area of old growth by biogeoclimatic zone		
		• Distribution of selected habitat elements in Timber Harvesting Land Base by Landscape Unit by BEC variant by licensee over time	[19] [19]	
		• Number of invasive, alien, forest-associated species	[19]	
		• Location and dispersal of introduced species	[19]	
		• Degree of disturbance to native species caused by invasive species	[19]	
		• Percentage of noxious and uncontrolled weeds in grass seed mixtures applied	[19]	
		• Percentage of introduced species in the Timber Harvesting Land Base by Landscape Unit	[19] [19]	
		• Number of native forest-associated species	[19]	
		• Status of in situ and ex situ efforts focused on conservation of species diversity	[19]	
		• Tree species and size	[19]	
		• Forest dwelling species for which ecological information is available	[19]	
		• Forest dwelling species for which ecological information is available	[19]	
		• Size of parent population having produced regeneration	[19]	
		• Change in the amount of certified seed-producing stands		
		• Area of natural and man-made forests	[19]	
		• Status of in situ and ex situ efforts focused on conservation of genetic diversity	[19]	
		• Changes in genetic diversity of species undergoing selective pressures	[19]	
		• Amount of genetic variation within and between populations of representative forest-dwelling species	[19]	
		• Changes in population, genetic diversity and structure, and gene flow for selected species	[19]	
		• Number and geographic distribution of forest-associated species at risk of losing genetic variation and locally adapted genotype		
		• Status of sensitive ecosystems with reduced ranges		
		• Population levels of selected representative forest-associated species to describe genetic diversity		
		• Extent of native forest and plantations of indigenous species which have genetic resource cons. plans prepared and implemented		
		• Forest associated species at risk from isolation and the loss of genetic variation, and conservation efforts for those species		

	Sustainability aspect	Sustainability parameter	Reference discussing the sustainability parameter	Case study using the sustainability parameter
	Impact on bioproductivity	• Maintain or improve soil physical, chemical, and biological conditions • Exceed levels of rate of harvest which can be permanently sustained • Maintain ecosystem functions and services including: a) regeneration and succession. b) Genetic, species, and ecosystem diversity. c) Natural cycles that affect the productivity of the ecosystem. • Total growing stock and annual increment of merchantable and non-merchantable tree-species in forests available for production • Percentage of and extent of cover types and maturity classes • Mean Annual Increment (MAI) by • Species distribution of growing stock (THLB and non-contributing areas) by Natural Disturbance Type (NDT) and • Annual harvests of non-timber forest products relative to the levels of harvests deemed to be sustainable • Loss of the Timber Harvesting Land Base to roads, seismic lines, well sites, and other developments • Area (ha) removed due to inoperability • Additions and deletions of forest area, by cause • Area (ha) reclassified (see also Loss of the THLB to roads, seismic lines, well sites, and other developments) • Proportion of timber harvest area successfully regenerated • Area out of compliance with free-to-grow objectives • Areas (ha) treated by treatment type by licensee including commercial thinning, fertilization, and pesticides • Records of assessment of the productive capacity for existing non-wood products • Annual harvest of wood products by volume and as a percentage of net growth or sustained yield • Annual harvest of non-wood forest products • Carrying capacity of the system for economically important species • Area and percent of forest land and net area of forest land available for wood production • Area, percent, and growing stock of plantations of native and exotic species • Native forest available for wood production, area harvested, and growing stock of merchantable and non merchantable tree species • Annual Removal of non-wood forest products compared with the level determined to be sustainable	[15] [14] [14-15] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19]	[20]
	Quality of environmental management system	• Implement good practices for the storage, handling, use, and disposal of chemicals • Water management plan which aims to use water efficiently and to maintain or enhance the quality of the water resources • Complete assessment of environmental impacts -- appropriate to the scale, intensity	[15] [15]	

	Sustainability aspect	Sustainability parameter	Reference discussing the sustainability parameter	Case study using the sustainability parameter
		of the affected resources -- and adequately integrate into management systems. • Prepared and implemented written guidelines to: control erosion; minimize damage during harvesting, road construction, and all other mechanical disturbances; and protect water resources. • Promote the development and adoption of 'environmentally friendly' non-chemical methods of pest management and strive to avoid the use of chemical pesticides. • Document, minimize, monitor and strictly control the use of biological control agents in accordance with national laws and internationally accepted scientific protocols • Prohibit the use of genetically modified organisms • Control and actively monitor the use of exotic species to avoid adverse ecological impacts • Provide the management plan and supporting documents a) Management objectives. b) Description of the forest resources to be managed, environmental limitations, land use and ownership status, socio-economic conditions, and a profile of adjacent lands. c) Description of silvicultural and/or other management system, based on the ecology of the forest in question and information gathered through resource inventories. d) Rationale for rate of annual harvest and species selection. e) Provisions for monitoring of forest growth and dynamics. f) Environmental safeguards based on environmental assessments. g) Plans for the identification and protection of rare, threatened and endangered species. h) Maps describing the forest resource base including protected areas, planned management activities and land ownership. i) Description and justification of harvesting techniques and equipment to be used • Revise the management plan periodically to incorporate the results of monitoring or new scientific and technical information, as well as to respond to changing environmental, social and economic circumstances. • Monitor procedures consistent and replicable over time to allow comparison of results and assessment of change. • Research and data collection of the following indicators: a) Yield of all forest products harvested. b) Growth rates, regeneration and condition of the forest. c) Composition and observed changes in the flora and fauna. d) Environmental and social impacts of harvesting and other operations. e) Costs, productivity, and efficiency of forest management. • Incorporate the results of monitoring into the implementation and revision of the management plan. • Include and implement specific measures that ensure the maintenance and/or enhancement	[14] [14] [14] [14] [14] [14] [14] [14] [14] [14] [14] [14] [14] [14] [14]	

	Sustainability aspect	Sustainability parameter	Reference discussing the sustainability parameter	Case study using the sustainability parameter
		of the applicable conservation attributes consistent with the precautionary approach. • Conduct annual monitoring to assess the effectiveness of the measures employed to maintain or enhance the applicable conservation attributes. • State the management objectives of the plantation, including natural forest conservation and restoration objectives in the management plan, and clearly demonstrated in the implementation of the plan. • Promote the protection, restoration and conservation of natural forests • Promote diversity in the composition of plantations to enhance economic, ecological and social stability • Select species for planting based on their overall suitability for the site and their appropriateness to the management objectives. In order to enhance the conservation of biological diversity, native species are preferred over exotic species in the establishment of plantations and the restoration of degraded ecosystems. Exotic species used only when their performance is greater than that of native species, carefully monitored to detect unusual mortality, disease, or insect outbreaks and adverse ecological impacts.	[14]	
	Good international technical practice	• Good practices for contained burning of residues, wastes or byproducts to maintain emissions of air pollutants below national and international norms • Minimize the risk of damages to environment and people, and improve environmental and/or social performance over the long term by the technologies used including genetically modified: plants, micro-organisms, and algae • Manage residues, wastes and byproducts so that soil, water and air physical, chemical, and biological conditions are not damaged. • Maintain or improve soil structure, fertility, and biological activity.	[15] [15] [15] [14]	
	Risk of severe environmental accidents	• Adequately contain micro-organisms which may represent a risk to the environment or people to prevent release into the environment • Protect areas from illegal harvesting, settlement and other unauthorized activities. • The abuse and risk potential	[15] [14] [4]	
Social impac	**Safety and health impacts**	• Assess risks to food security in the region and locality • Enhance local food security in food insecure regions • Occupational and commuting accidents • Fatal occupational and commuting accidents • Occupational diseases	[15] [15] [23] [23] [23]	
	Quality of safety and health management system	• Incorporate the results of evaluations of social impact	[14]	

	Sustainability aspect	Sustainability parameter	Reference discussing the sustainability parameter	Case study using the sustainability parameter
t	**Good international practice regarding safety and health**	• Follow internationally recognised standards of occupational safety and health for workers. • Meet or exceed all applicable laws and/or regulations covering health and safety of employees and their families.	[15] [14]	
	Risks of severe safety or health accidents	• Toxicity potential • Additional health risks (e.g. danger of accidents, addiction)	[23]	
	Adherence to social rights	• Freedom of association, the right to organise, and the right to collectively bargain. • Occurrences of slave labour or forced labour • Occurrences of child labour, exception to family farms and then only when work does not interfere with the child's schooling and does not put his or her health at risk • Discrimination of any kind, whether in employment or opportunity, with respect to wages, working conditions, and social benefits • Equal remuneration for work of equal value • Assess, document, and establish existing land rights and land use rights • Ensure no issues relating to use rights, land rights or traditional rights including issues of equitable compensation are pending • Demonstrate clear evidence of long-term use rights to the land (e.g. land title, customary rights, or lease agreements) • Employ appropriate mechanisms to resolve disputes over tenure claims and use rights • Wages and salaries male • Wages and salaries women • Company expenditures for social security • Wages and salaries • Company benefits such as housing subsidies, workforce facilities, payments in kind and cafeteria subsidies • Company expenditures for family support • Benefits for disadvantaged people (e.g. disabled, sick, poor) due to product quality • Strikes and lockouts • Indigenous peoples control their lands and territories unless they delegate control with free and informed consent to other agencies • Threaten or diminish, either directly or indirectly, the resources or tenure rights of indigenous peoples.	[14-15, 23] [15, 23] [15, 23] [15, 23] [15] [15] [15] [14] [14] [1] [1] [23] [23] [23] [23] [23] [23] [14] [14]	
	Complying with company code of conduct			
	Quality of human and labour rights management system	• Form the basis for the process to be followed during all stakeholder consultation, gender sensitive and result in consensus-driven negotiated agreements • Comply with all applicable laws and international conventions for wages and working conditions • Comply with all relevant collective agreements • Implement a mechanism to ensure the human rights and labor rights outlined in this principle apply equally when labor is	[15] [15] [15] [15] [15] [19]	

	Sustainability aspect	Sustainability parameter	Reference discussing the sustainability parameter	Case study using the sustainability parameter
		contracted through third parties • Form the basis for all negotiated agreements for any compensation, acquisition, or voluntary relinquishment of rights by land users or owners • Number of education and training programs • Instances of significant non-compliance with Forests and Range Practices Act • Incidents of and fines for non-compliance (international, national, sub-national, regional, local)* • Presence of certification implementation committee (e.g SFI Implementation Committees) • Presence of certification implementation committee (e.g SFI Implementation Committees) • Number of complaints to Forest Practices Board (FPB) versus number addressed • Extent to which the institutional framework provides for public involvement activities and public education programs... • Extent to which the institutional framwork has the capacity to undertake and implement planning, assessment and policy review • Extent to which the institutional framework develops and maintains • Capacity to develop and maintain • Extent to which the institutional framework includes the capacity to enforce laws, regulations and guidelines • Measuring and Monitoring	[19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19]	
	Social differentiation	• Employment male • Employment women • Number of employees • Number of unskilled workers (qualification of workers) • Number of female managers • Number of disabled employees • Number of part-time workers	[1] [1] [23] [23] [23] [23] [23]	
	Impact on surrounding communities	• Improve regions of poverty, the socioeconomic status of local stakeholders impact • Benefit and encourage the participation of women, youth and indigenous communities • Respect the existing water rights of local and indigenous communities • Local communities with legal or customary tenure or use rights maintain control, to the extent necessary to protect their rights or resources, unless they delegate control with free and informed consent to other agencies. • Give opportunities for employment, training, and other services to the communities within, or adjacent to • Resolve grievances and for provide fair compensation in the case of loss or damage affecting the legal or customary rights, property, resources, or livelihoods of local peoples • Area of forest land owned by Aboriginal peoples • Number of tenures offered to First Nations	[15] [15] [15] [14] [14] [14] [19] [19] [19] [19] [19]	

	Sustainability aspect	Sustainability parameter	Reference discussing the sustainability parameter	Case study using the sustainability parameter
		• Extent of Aboriginal participation in forest-based economic opportunities	[19] [19]	
		• Aboriginal Employment	[19]	
		• Revenue generated by Aboriginal businesses in timber products industry	[19] [19]	
		• Number of Aboriginal communities that have a significant forestry component	[19] [19]	
		• Number of joint ventures and/or co-managed forests	[19]	
		• Contract total paid to First Nations Bands	[19]	
		• Number of opportunities for First Nations involvement	[19] [19]	
		• Degree of satisfaction with contract development process	[19] [19]	
		• Local representative in provincial or federal government	[19] [19]	
		• Area of forest land managed primarily for the protection of domestic water supply	[19] [19]	
		• Water Consumption	[19]	
		• Cost-effective delivery of drinking water	[19]	
		• Expenditures (monetary and in-kind) on restoration activities	[19] [19]	
		• Watersheds that support water licenses	[19]	
		• Watersheds that support water licenses	[19]	
		• Resillience of forest-dependent communities	[19]	
		• Index of social structure quality	[19]	
		• Migration history, likelihood of future migration	[19]	
		• Social capital infrastructure	[19]	
		• Rates of entrepreneurship	[19]	
		• Population mental health rate	[19]	
		• Infant mortality rate	[19]	
		• Mortality rate	[19]	
		• Life expectancy	[19]	
		• Cancer	[19]	
		• Low birth weights	[19]	
		• Education attainment levels in forest-based communities	[19]	
		• Composition of senior management and corporate governance bodies	[19] [19]	
		• Incidence of low income in forest-based communities	[19]	
		• Business and property values	[19]	
		• Average household income	[19]	
		• Composition of income	[19]	
		• Poverty rate		
		• Crime rates	[19]	
		• Access/use of social services	[19]	
		• Income distribution		
		• Contributing time and money to charities and non-profit organizations (volunteerism)	[19] [19]	
		• Membership in organizations	[19]	
		• Participation in community sustainability initiatives	[19] [19]	
		• Presence of holistic forest management (integrated resource management, adaptive co-management) practices	[19] [19]	
		• Racial discrimination		
		• The importance of forests to people	[19]	
		• Presence and quality of First Nations information sharing and referrals programs	[19]	
		• Areas where treaty or Aboriginal rights are being practiced	[19]	

	Sustainability aspect	Sustainability parameter	Reference discussing the sustainability parameter	Case study using the sustainability parameter
		• Extent of incorporation of First Nations knowledge in cultural inventories • Documentation of property and use rights • Area of forest Crown land with traditional land-use studies • All uses of traditional knowledge are documented • Area of First Nations traditional use sites by type • Percentage of cut-blocks by band where agreement is reached around the management • Aboriginal income derived from TEK • Number of traditional land users and income earned from traditional land use • Level of incorporation of First Nations traditional roles and systems into forest management plans • Management framework maintains and enhances Indigenous values use • Technical, logistical and cross-cultural capacity exists to enable informed and meaningful engagement in forest management plans	[19]	
	Impact on culture and recreation	• Potential of intensification of social and political conflicts (e.g. due to changes of traditional lifestyles) • Clearly identified sites of special cultural, ecological, economic or religious significance to indigenous peoples • Monitor plantations include regular assessment of potential on-site and off-site ecological and social impacts, (e.g. natural regeneration, effects on water resources and soil fertility, and impacts on local welfare and social well-being) • No species planted on a large scale until local trials and/or experience have shown that they are ecologically well-adapted to the site, are not invasive, and do not have significant negative ecological impacts on other ecosystems. Special attention will be paid to social issues of land acquisition for plantations, especially the protection of local rights of ownership, use or access. • Areas suitable for recreation expansion through inventory • Contribution of the tourism sector to area and provincial economy • Number of recreational user days • Road density index within recreation zone • Cost of maintenance activities in recreation tourism zone • Sites and features of cultural significance are identified, mapped, discussed and protected* • Outfitting Revenue • Area and percent of forests available and/or managed for public recreation and tourism • Number, type, and geographic distribution of visits attributed to recreation and tourism and related to facilities available • Proportion of forests sites available for recreation and tourism, which are impacted	[23] [14] [14] ‘ [14] [19] [19] [19] [19] [19] [19] [19] [19] [19]	

	Sustainability aspect	Sustainability parameter	Reference discussing the sustainability parameter	Case study using the sustainability parameter
		unacceptably by visitors		
	Build life cycle thinking and practices into every day work			
	Satisfying product function	• Extra benefits that enhance customer satisfaction (e.g. service, increase in leisure time, low noise) • Completeness and quality of product information (about origin, ingredients, use, potential danger, side-effects, etc.) • Potential of misuse of products (e.g. as a weapon)	[23] [23] [23]	
	Competence development of co workers	• Number of trainees • Expenditures for professional training and continuing education • Receive adequate training and supervision to ensure proper implementation of the management plan.	[23] [23] [14]	
Economic impact	**Adherence to existing or future regulations**	• Comply with all applicable laws and regulations • Assess impacts and risks and ensure sustainability through the development of effective and efficient implementation, mitigation, monitoring and evaluation plans • Respect all national and local laws and administrative requirements • Pay all applicable and legally prescribed fees, royalties, taxes and other charges • Respect in signatory countries, the provisions of all binding international agreements • Evaluate conflicts between laws, regulations and principles and criteria for the purposes of certification, on a case by case basis, by the certifiers and the involved or affected parties • Legal framework • Extent of consultation with Aboriginals in forest management planning and in the development of policies and legislation • Level of First Nations satisfaction with involvement in development of forest management policies, legislation, and agreements • Extent to which forest planning and management consider and meet legal obligations of Aboriginal and treaty rights • Recognizes and respects the legal and customary rights of First Nations over their lands, territories, and resources • Absence of unsolved disputes on legal, tenure, or use rights • Number of incidences of non-compliance with treaty settlements and Interim Measures Agreements • Participation in planning • Proportion of participants who are satisfied with public involvement processes in forest management in • Number of communications (operational) by interest group, by type by licensee	[15] [15] [14] [14] [14] [14] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19]	

	Sustainability aspect	Sustainability parameter	Reference discussing the sustainability parameter	Case study using the sustainability parameter
		• Percentage of comments receiving response by type by licensee • Response by licensees to public comments/participation • Legal framework provides opportunities for public participation in policy and decision-making related to forests • Forest management plans made public, with respect to confidentiality • Rate of compliance with sustainable forest management laws, regulations, and best management practices • Extent of mitigative action when ecosystems, culturally important areas, and traditional resources are damaged • Proactive consultation process for significant activities such as proposed timber harvesting • Evidence that community feedback was considered in management planning • Status of new or updated forest management guidelines and standards related to ecological issues • Percent of forest management commitments completed resulting from consultation about non-timber features and interests* > • The legal framework clarifies property rights, provides for appropriate land tenure arrangements, recognizes customary... • Extent to which the legal framework provides for planning, assessment, and policy review that recognizes multiple forest values • Extent to which the legal framework encourages best practice codes for forest management • ...the legal framework provides for the management of forests to conserve environmental, cultural, social, scientific values • Extent to which the legal framework supports the conservation and sustainable management of forests	[19] [19] [19] [19] [19]	
	Availability of raw materials	• Sawmill Lumber Recovery Factor, Chip Recovery Factor, and shipment of mini-chips • Timber Price Trend • The value of forage harvested from rangeland by livestock • Wildlife harvested • Fish harvested • Volume by type of Non-timber Forest Product (NTFP) (m3, kg) • Contribution of timber products to the Gross Domestic Product (GDP) • Value and volume of wood and wood products production, including primary and secondary processing • Production, consumption, imports, and exports of timber products • Contribution of non-timber forest products and forest-based services to the gross domestic product • Value of unmarketed non timber forest products and forest-based services • Revenue from forest based environmental	[19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19]	

	Sustainability aspect	Sustainability parameter	Reference discussing the sustainability parameter	Case study using the sustainability parameter
		services • Value and volume in round wood equivalents of exports and imports of wood products • Value of exports and imports of non-wood products • Exports as a share of wood and wood products production and imports as a share of wood and wood products consumption • Recovery or recycling of forest products as a percent of total forest products consumption • Return on capital employed • Productivity Index • Value of non-wood forest products produced or collected • Total and per capita consumption of wood and wood products in round wood equivalents • Total and per capita consumption of non-wood products	[19] [19] [19] [19] [19] [19] [19] [19]	
	Assets needed	• Capital investment • Investment as percent of GDP • Ratio of stumpage charge to wood product prices • Stumpage Paid • Public and private funding for research, educational, and extension programs • Annual investment and expenditure in forest-related research, extension and development, and education • Capital investment and annual expenditure in forest mgmt., wood and non-wood products, environmental services, recreation... • Extension and use of new and improved technologies • Rates of return on investment • Investment in research, development, extension and use of new and improved technologies.	[23] [19] [19] [19] [19] [19] [19] [19] [19] [19]	
	Operating costs	• Cost of raw materials from forest wood chain • Cost of raw materials from outside forest wood chain • Labour cost • Cost of energy • Other productive costs • Other non-productive costs • Material costs • Compensated indigenous peoples for the application of their traditional knowledge • Existing tenures (forest tenures and other types of tenure) • Opportunities for allocation of community-based tenures • Value of contracts issued by demographic class • Economic Sustainability (delivered in wood costs C$/m3) • High-use rates of local wood processing capacity • Total person days and jobs per cubic metre • Total payroll and benefits by country/region • Employment diversity • Forest area by timber tenure • Distribution of revenues derived from forest	[1] [1] [1, 4] [1, 4] [1] [1] [4] [14] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19] [19]	

	Sustainability aspect	Sustainability parameter	Reference discussing the sustainability parameter	Case study using the sustainability parameter
		management		
		• Employment in the forest sector	[19]	
		• Average wage rates, annual average income and annual injury rates in major forest employment categories	[19] [19]	
		• Economic diversity index of forest-based communities	[19]	
		• Distribution of expenditures locally		
		• Size of labour pool	[19]	
		• Number of households with forest-based employment (full- or part-time)	[19]	
		• Annual harvest compared to local log consumption that is provided	[19] [19]	
		• Contract total paid to local enterprise		
		• Employment rate in forest-based communities	[19]	
		• Gender-related indices in forestry (gender-related development index in human development reports of the UNDP)		
		• Accident rates		
		• Standard injury, lost day, and absentees rates and numbers of work-related fatalities (including subcontracted workers)		
		• Area and percent of forests used for subsistence purposes sustainable forest Management and implications for poverty alleviation		
	Market differentiation	• Violation of ethical norms due to product use or advertisement	[23]	
		• Expenditures for R&D	[23]	
		• Sum of import duties and export subsidies (protectionism)	[23] [23]	
		• Imports from developing countries	[23]	
		• Fair trade labels etc.	[23]	
		• Consumer labels (e.g. 'EU flower')	[19]	
		• Number of research partnerships	[19]	
		• Area of Forest under SFM Plans		
		• Number of SFM-related research projects initiated and/or completed by type	[19]	
		• Applied social and natural science research which addresses issues of local and regional significance	[19] [19]	
		• Extension	[19]	
		• Capacity to conduct and apply research and development including the scientific understanding of forest ecosystems...	[19]	
		• Development of methodologies to measure and integrate environmental and social costs and benefits into markets and public policy	[19]	
		• New technologies and the capacity to assess the socio-economic consequences associated with the introduction of new technologies	[19]	
		• Enhancement of ability to predict impacts of human intervention on forests	[19]	
		• Capacity to conduct research and development including the ability to predict impacts on forests of possible climate change	[19]	
		• Community participation in sustainable Forest Management		
	Price of product	• Food price	[24-26]	

	Sustainability aspect	Sustainability parameter	Reference discussing the sustainability parameter	Case study using the sustainability parameter
	Quality of quality management system	• Implement a business plan that reflects a commitment to long-term economic viability • Account the full environmental, social, and operational costs of production, and ensuring the investments necessary to maintain the ecological productivity • Encourage the optimal use and local processing of the forest's diversity of products • Extent to which the economic framework supports the management of forests through Investment and taxation policies... • Extent to which the economic framework supports Non-discriminatory trade policies for forest products • Compatibility with other countries in measuring, monitoring, and reporting on indicators • Coverage, attributes, frequency, and statistical reliability of forest inventories • Existence or a repeated forest inventory at the scale of the province • Capacity to measure and monitor changes...including the availability and extent of up-to-date data • Cost of acquiring data or level of access fee for forest inventory information • Scope, frequency and statistical	[15] [14] [14] [19] [19] [19] [19] [19] [19] [19] [19]	
	Technical quality factors	• Minimise waste associated with harvesting and on-site processing operations and avoid damage	[14]	
	Threats regarding public's perception of the product			
	Governance / transparency and accountability	• Fully available information on the use of technologies in, unless limited by national law or international agreements on intellectual property	[15]	
	Working transparently with our stakeholders	• Demonstrate a long-term commitment • Strive to strengthen and diversify the local economy, avoiding dependence on a single product. • Make a summary of the primary elements of the management plan publicly available • Provide documentation to enable monitoring and certifying organizations to trace each product from its origin, a process known as the "chain of custody." • Make a summary of the results of monitoring indicators publicly available	[14] [14] [14] [14] [14]	

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Paper I

Accepted manuscript

Changing from petroleum to wood-based materials: critical review of how product sustainability characteristics can be assessed and compared

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Abstract

This paper reports on a literature survey on available approaches for the assessment of product sustainability, with a specific focus on assessing the replacement of non-renewable petroleum-based materials with renewable wood-based materials in absorbent hygiene products. The results are contrasted to needs in a specific material development project.

A diverse number of methods exist that can help in assessing different product sustainability characteristics for parts of or whole product lifecycles. None of the assessment methods found include guidelines for how to make a case-specific interpretation of sustainability and there is a general lack of assessment parameters that can describe considerations in the comparison between the use of wood or petroleum as main raw material. One reason for this is lack of knowledge and/or consensus on how to describe and assess impacts of land and water use, e.g. on ecosystem services, different types of resource depletion and social impacts.

Keywords

Non-renewable resources, Renewable resources, Sustainability assessment, Life cycle perspective, Sustainable resource management, Material development, Diaper, Nappy, Absorbent hygiene product

1. Introduction

Due to different concerns, such as diminishing reserves of non-renewable resources and increasing evidence of climate change related to emissions of green house gases (GHGs), many companies are shifting from non-renewable to renewable material resources, expecting that this will result in more sustainable products. However, the sustainability of products is a complex issue that depends on numerous factors; renewability and climate change are only two of these. Changing from a non-renewable to a renewable raw material does not automatically mean that the product will become more sustainable. The material from a renewable resource might, for instance, need more energy in the production stage, or more material might be required for the final product to fulfil its function in a satisfactory way, than if a non-renewable material resource had been used; a situation that has been discussed rather extensively in relation to biofuels, e.g. ethanol (Farrell et al., 2006; Fehrenbach et al., 2008). Therefore, in the short- to mid-term, before we actually run out of a specific fossil resource, it might in some cases be a better choice to continue to use the fossil resource until suitable materials, improved technologies, or new use patterns have been developed. In fact, it comes down to how 'sustainability' is interpreted in each specific comparison.

With increasing competition for resources following increasing global consumption, resource use needs to a greater extent be valued based on resource limitations and potential competition from other areas of use. In the case of the non-renewable resource petroleum versus the renewable resource wood as a raw material for different products, this could come down to weighing the depletion of limited petroleum resources against increasing land area requirements, including different impacts from the cultivation of wood resources and direct and indirect impacts from land use change. In any such assessment, impacts need to be related to the specific functions that are ultimately fulfilled in society by the product; therefore, a life cycle perspective is necessary, with the product´s function as the point of reference. This will ensure that sustainability impacts throughout the product´s entire life cycle are considered and that changes that just shift the burden from one stage to another can be avoided.

This study has been performed within the WooDi (the Wood Based Diaper) project, which aims to develop wood-based materials that can replace petroleum-based materials in the absorbent core of a diaper. The research project is a collaboration between industry and university. The goal of the project is that a diaper containing the new materials should be more sustainable than a reference diaper based on present technology. This calls for a methodology that will allow assessing and comparing the sustainability impacts associated with using these different resources in a product.

Munthe, in a report to the Swedish Agricultural Administration in 1997 (Munthe, 1997), defined three questions that should be answered before any assessment effort is started:

- What concerns should be included?
- How should potential trade-offs between the concerns be made?
- How should uncertainties in the required information be handled?

Munthe argued that these questions need to be answered in order to ensure transparency and to avoid being influenced by expected or desired results.

The same type of questions have also been highlighted by others in comparing products, e.g. by Steen in 2006 (Steen, 2006), and they are most likely useful as a basis in any product assessment. The three questions can be formulated in the following way for the WooDi project: (1) What sustainability considerations are essential to include in the product assessment, taking into account the specifics of the product systems under study and the challenges that emerge in light of world development and the goal of sustainable development (i.e. which assessment parameters are the most relevant to include)? (2) How should potential trade-offs between these sustainability concerns be handled if the compared sustainability profiles peak in different areas (i.e. what weighting factors should be used)? and (3) How should the yet unknown final product and product system be dealt with in a sustainability assessment?

Since the WooDi project deals with material development, many features of the final product are still unknown, at least early on in the project. Over time, more characteristics of the final product will be possible to estimate and the full product system will eventually be possible to discern. Throughout this material development process, the sustainability assessment approaches that are the most appropriate to employ will likely shift as the needs of the project change. In order to ensure that the new product is developed to become more sustainable than the reference product, the new ideas must, despite the original uncertainties, be benchmarked to a reference product that already exists on the market. The people making important choices in this process need therefore be guided through the important considerations, starting with awareness-raising exercises and working towards a quantitative to semi-quantitative comparison.

This paper reports on available literature on defining, assessing and comparing the sustainability of products made from renewable (wood-based) respectively non-renewable (petroleum-based) materials, specifically for products or activities that are of relevance for the WooDi project, i.e. absorbent materials in diapers and other hygiene products. Knowledge and methodology gaps that need to be filled in order for a sustainability comparison to be performed within the WooDi project are discussed.

2. Research method

In order to provide information to the WooDi project, which aims at achieving a shift from petroleum to wood as the material base for the absorbent core of an incontinence diaper, a literature survey was carried out on available sustainability impact assessment approaches. Besides creating an overview of existing assessment approaches that could prove useful in the project, an emphasis was put on exploring which assessment parameters that have been in actual use in assessing materials of fossil and biological origin and how these parameters have been selected, in order to provide input to the comparative assessment that is to be conducted within the WooDi project. By contrasting the results from the survey with the needs of the WooDi project, existing gaps in knowledge and methodology were evaluated and further steps that need to be taken were identified.

Regarding approaches and techniques for the assessment of environmental sustainability from a systems perspective, an overview has been published earlier by other authors (CHAINET, 2002). In the present paper, the investigation was narrowed down to what is most urgently needed in the WooDi project, i.e. the state-of-the-art in terms of comparing the sustainability characteristics of products made from petroleum-based and wood-based materials.

Figure 1 provides an overview of the ideas underlying the present study and the type of results that will be reported on in this paper. Different approaches found in literature have been classified according to the CHAINET nomenclature regarding assessment approaches for the environmental dimension of sustainable development (CHAINET, 2002; Wrisberg et al., 2002); ‘analytical approaches’ are mainly employed to assess the impact of a product system, while ‘procedural approaches’ primarily focus on determining whether certain requirements are fulfilled.

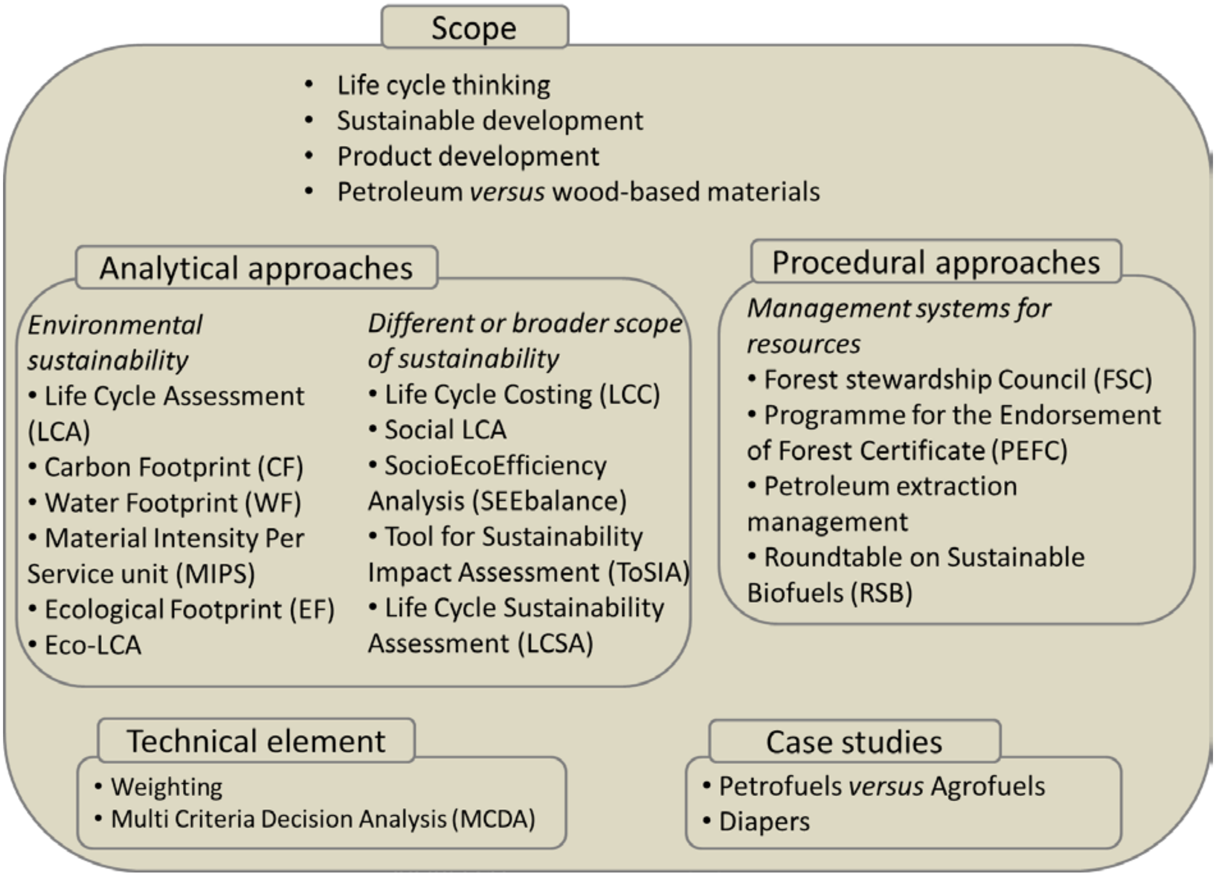

Figure 1. An overview of approaches and techniques discussed in this paper.

In Figure 1, the 'scope' summarises underlying theories and delimitations of this study, as discussed in the previous section. In Section 3, analytical approaches that assess the life cycle performance of products based on one or several environmental parameters are reviewed, including issues related to weighting and also some analytical approaches with a broader, more holistic, scope. In Section 4, procedural approaches such as certification schemes for different resources and biofuels are reviewed. These often include assessment parameters important for resource extraction or cultivation stages which are normally not considered in e.g. life cycle assessments due to the difficulty in measuring things like biodiversity and social progress. In Section 5, case studies, in which products with petroleum and biomass-based materials are compared and reviewed along with case studies assessing diapers. Finally, in Section 6, an overview of sustainability assessment parameters and their use is given and how the different analytical and procedural approaches can be used in the WooDi project is discussed. Only approaches and results relevant to the WooDi project are reported on, i.e. they deal with the sustainability assessment of products and resources and provide input to making a comparison of the use of petroleum and wood-based materials.

3. Analytical approaches for assessing the life cycle performance of products

3.1. Environmental performance

Life Cycle Assessment (LCA) methodology is widely used to evaluate the environmental performance of product systems. An LCA studies potential environmental impacts of a product or service throughout its life, from resource acquisition through production, use and waste management, by mapping and evaluating flows crossing the system boundary, see for example Pennington et al. and Rebitzer et al. for a more thorough description of LCA methodology (Pennington et al., 2004; Rebitzer et al., 2004). LCA is a standardised method for the environmental assessment of products, included in the ISO 14040 series. An LCA should include the whole life cycle and should look at as many environmental impacts (ecological consequences, resource use and impacts on human health) as necessary to comprehensively reflect the goal and scope of the study. In most cases, only a few selected impact categories and a limited part of the total life cycle are considered. The goal and scope definition is extremely important since the LCA will mainly answer the questions it is designed to answer. Given that different LCAs have different objectives, it is often impossible to directly compare their results. LCA approaches that focus on a specific impact category are for example the Carbon Footprint (CF), the Water footprint (WF) and the Material Input Per Service unit (MIPS).

Depending on the scope of the LCA, different modeling approaches can be utilized, and this can strongly influence the results, for example if the study is attributional or consequential, and how and to what extent system expansion has been used (Earles and Halog, 2011). The system expansion methodology can add substantially to the understanding of potential consequences of a proposed change, but at the same time, the system model will be even more complex and often more difficult to grasp. For bio-based materials, a relevant example is for land use. In an attributional study, the land that is needed for the biomass production will be included together with any direct environmental impacts from using the land. In a consequential study also indirect land use changes will be included, e.g. when displaced activities lead to land use change in other areas (Earles and Halog, 2011). It has been suggested that scenario modeling could support a consequential study in providing a more complete description of the potential consequences (Zamagni et al., 2012).

3.1.1 Assessment of specific impact categories

For comparisons between products based on renewable and non-renewable resources, there are some potentially relevant impact categories that have received special attention.

The *Carbon Footprint* (CF) is a concept that has gained interest in recent years, with the increased public concern for climate change (Wiedmann and Minx, 2007). The CF reports on the overall amount of carbon dioxide emissions and in more rigorous studies also other GHG emissions (e.g. methane and nitrous oxide), associated with a product. Basically, it is an LCA that focuses solely on carbon dioxide or on GHGs. Disparities in the definition of this rather commonly used concept have led to standardisation efforts, resulting in the British standard PAS 2050 (PAS 2050, 2008). Besides the GHG emissions from technical activities during a life cycle, this standard includes how to calculate emissions from direct land use change due to increased use of biomass resources. Direct land use change refers, for example, to the conversion of non-agricultural land to agricultural land as a consequence of increased production of agricultural products, which typically deteriorates the carbon storage capacity of the soil. This is of great importance, e.g. for biofuel production chains; failing to consider this might overestimate climate benefits (Bringezu et al., 2009b; Börjesson and Tufvesson, 2011). If the biological feedstock is instead produced on degraded soil, with low original carbon storage capacity, it can potentially contribute to an improvement of the soil carbon storage capacity. The impact of indirect land use change, i.e. land use change induced in other areas is, however, not yet included in PAS 2050. This is due to the lack of data; otherwise very few CF analyses would be able to comply with the standard. Efforts to account for indirect land use change can be found in the literature (Cornelissen and Dehue, 2009; Gnansounou et al., 2008b; Searchinger et al., 2008). It is likely that the new materials developed within the WooDi project will lead to an increase in the use of forest biomass for incontinence protection and both direct and indirect land use changes could be relevant to assess.

Awareness of that fresh water is a limited global resource has increased in recent years, resulting in the concept of *Water Footprint* (WF). A product's WF is defined as the total volume of fresh water used, directly or indirectly, to produce the product (Hoekstra et al., 2009; Water Footprint Network). The WF of a product is divided into green, blue and grey water, where green water refers to rainwater stored in the soil as soil moisture, used for plant growth, blue water refers to surface and ground water for technical use in processes or for irrigation, and grey water refers to polluted water and is defined as the volume of freshwater needed to dilute the water to pollutant levels required by existing water quality standards (Hoekstra et al., 2009). There are ongoing efforts to establish practises for how to include water use in established LCA procedures, e.g. the WUCLA project within the UNEP/SETAC Life Cycle Initiative (Kounina et al., 201X). In WooDi, the production of wood-based materials is assumed to take place in the Nordic countries. Water is normally not seen as a scarce resource in the Nordic countries, however, a small water footprint could still be useful or even important when promoting the product in other countries. Water pollution relating to both petroleum and wood acquisition as well as to different production processes, might be important to include in the WooDi project and the categories in the WF could prove useful as assessment parameters.

Material Input Per Service unit (MIPS) is a material flow accounting method with products or services as study objects (Ritthoff et al., 2002). Impacts throughout the whole life cycle are considered, however, MIPS focuses only on the input side. The argument is that all material input will eventually become an output, e.g. waste or emission. Therefore, by measuring the input, one can arrive at an estimate of the potential environmental impact. MIPS calculates the use of resources from the point of their extraction from nature, i.e. the tonnes of moved renewable raw materials, non-renewable raw materials, water or air. All material consumption should be traced back to primary resource consumption. MIPS is unspecific to particular materials and therefore does not include substance-specific hazards. For the WooDi project, MIPS might be a method for early screening of the amount of renewable and non-renewable resources used for the different diapers as well as one of the assessment parameters in the final sustainability assessment, however, it has to be complemented with parameters that can provide greater level of detail of the potential impacts of the input flows and also of the output flows.

Biomass resource use has impacts on land resources, for example as occupied land area or changes in soil quality. Since biomass resource use might increase if diapers, to a larger extent, are produced from wood resources, this should be considered in the WooDi sustainability assessment. In an LCA, the fact that land area is a limited resource is generally not taken into account. If included, it is usually as land area occupation. The *ecological footprint* (EF) is a related concept that includes not only the occupied land but also involves a recalculation of other environmental impacts into potential land area occupation. This concept will therefore be discussed further also in Section 3.1.2 as a weighting method in LCA. Regarding land area, Helming et al. argue that even though land cannot be depleted from a spatial point of view, the possibility for different types of use of the land can be changed or depleted, hence land quality can be depleted (Helming et al., 2008). The manner in which land is used, often referred to as land use (IPCC, 2000), is a parameter that is rarely included in LCA studies, but the inclusion of impacts from land use into LCA has been proposed by several researchers (Antón et al., 2007; Mattsson et al., 1998; Mendoza and Martins, 2006; Michelsen, 2008; Swan, 1998; Vogtländer et al., 2004). In agricultural production, land use can be considered a very significant impact category due to its potential influence on soil quality and it has been applied in some studies of agricultural products (Mattsson et al., 2000). Biodiversity is one area that is strongly affected by land use, e.g. by loss, modification and fragmentation of habitats and the degradation of soil and water (Foley et al., 2005; MEA, 2005). To include biodiversity as an assessment parameter in LCA has been proposed, e.g. by Penman et al. (Penman et al., 2010), identifying the lack of a common definition of biodiversity as a main reason for the absence of measurable indicators. In order to include considerations of biodiversity in EF, a land area for biodiversity protection can be set aside, for example the 12% used in the original EF methodology presentation (Wackernagel and Yount, 1998) that was based on the Brundtland commission recommendations in 1987 in the report *Our Common Future* (WCED, 1987). The authors stated, however, that 12% might not be sufficient but they used it as a politically achievable share. A more recent UN-hosted initiative from 2009, intended to draw attention to the global economic benefits of biodiversity, suggests that a minimum of 15% of global land areas should be protected (TEEB, 2009). Berndes et al. conclude that how the use of land interacts with biodiversity, soil quality and global food, material and energy production needs to be defined and parameterised (Berndes et al., 2003). A proposed life cycle oriented approach that might be able to handle such issues is *Eco-LCA* (Baral et al., 2012; Zhang et al., 2010). Eco-LCA includes emergy analysis in describing consumption of natural resources such as ecosystem goods and services including biodiversity.

One difficulty with the land use aspect is thus that in order to provide meaning, it needs to be further parameterised into quantifiable entities regarding e.g. soil quality, biotic production potential and biodiversity. These impacts often interact with each other and how to quantify them in relevant ways will likely also vary with geographical conditions, which makes the evaluation complex (Milà i Canals et al., 2007); a lot of local data would be needed for the appropriate inclusion of land use in LCA. An LCA study that utilised detailed and site-specific land use inventories in a study of three vegetable oil crops highlighted erosion, soil organic matter, soil structure, soil pH, soil P and K status and impacts on biodiversity as important land use aspects (Mattsson et al., 2000). A recent review of developments in LCA stresses the need for further development on the impact assessment of land use (Finnveden et al., 2009). In assessing the sustainability impacts of the WooDi materials, land use and biodiversity issues should be addressed, but there is presently a lack of ready-to-use methods for doing so.

3.1.2 Weighting

In comparisons of the performance of two products, unless one product performs better than the other one for all selected assessment parameters, there is a need for the aggregation of results into a more holistic measure. There are several different weighting methods for environmentally related impacts with set weighting factors, commonly used in the LCA society. Some examples are Ecoscarcity 97, EDIP, Ecoindicator 99 and EPS2000 (Baumann and Tillman, 2004). Different methods are based on different value-systems and may provide different answers to which development routes are preferable. Finnveden concluded in 1999 that there is no single available pre-made method with set weighting factors that can be recommended, because they all suffer from different issues like significant data gaps, inconsistencies, or lack of justification of important assumptions (Finnveden, 1999). However, the use of weighting can still provide a greater understanding of LCA results (Bengtsson and Steen, 2000).

Several weighting methods available in literature include resource use in different ways. One example is the monetary values used by the Environmental Priority Strategies (EPS) method (Steen, 1999). Monetary values reflect the willingness to pay to safeguard the subjects human health, biological diversity, ecosystem production capacity, abiotic resources, and cultural and recreational values. The impact category for abiotic resources is the depletion of abiotic reserves; weighting factors for non-renewable resources are based on the cost of producing an equivalent amount from renewable resources and for renewable resources, weighting factors are based on their market price.

Other weighting methods like CML 2000, ReCiPe and IMPACT 2002 include non-renewable resources based on the 'resource to use' characterisation, where different resources are related to each other based on the ratio of the present speed of consumption over presently known reserves (European Commission, 2009a).

The EF methodology, estimating the biologically productive area needed to support current consumption patterns (Holmberg et al., 1999; Wackernagel and Rees, 1996), has generally been used for analysis of the impact of the consumption in nations and regions but can also be used as a weighting method in LCA (Wackernagel and Yount, 2000). The EF is calculated by translating all impacts from material and energy consumption and other activities, and land occupation, of, e.g. a product, a household, a local community, a region, or the whole of mankind, into area demand (measured in hectares). For example, a city not only occupies the actual ground that is covered by buildings and infrastructure; it also needs agricultural land, e.g. for food and fibre, sea area, e.g. for fishing, forest, e.g. to produce wood-based products and to assimilate CO_2 released from the combustion of petroleum fuels, and so forth. Thus, besides the area directly occupied, the material and energy use, and the generation of emissions and waste, have to be compiled and recalculated into an EF area, generally by multiplying by a land need index (Wackernagel and Yount, 1998). Such indices are calculated using LCA methodology. The EF thus recalculates resource use into area use, but it only considers renewable resource consumption. Including the consumption of non-renewable resources as an abiotic area use has been proposed (Nguyen and Yamamoto, 2007). The suggested approach includes resource depletion for metals but not for petroleum.

Some other methods do not include resource use, but instead rely on the assumption that the resource issue will be solved by the market, i.e. the price will depend on the availability of and the demand for the resource and therefore it does not need to be considered in the environmental assessment (Udo de Haes et al., 2002). In those cases, resource depletion is not seen as an environmental impact but rather as a social or economic one and is therefore omitted.

When it comes to product development for sustainable development, a method is needed that can guide in choosing resources that will not face severe restrictions exhibited by limitations on nature or society in the future, where resource use and resource availability will be different from today. There are many different methods and prototypes in diverse niche areas for assessing future products' or materials' life cycles or parts of life cycles

(Finnveden and Moberg, 2005; Höjer et al., 2008; Robèrt, 2000), but case studies in which they have been applied are rare.

It is generally recognised that the valuation element involved in weighting has to be based on political, ideological and/or ethical values and that these are influenced by people's perceptions and worldviews. Not only the individual weighting factors used in a specific method, but also the choice of valuation methodology and even the choice to use a weighting method at all, are influenced by fundamental ethical and ideological values (Finnveden, 1997).

Weighting can be made based on the opinions of participants in a weighting process, often with the major purpose of providing more structure and transparency to decision-making. It also offers the opportunity to introduce qualitative data and data outside of the environmental area. *Multi Criteria Decision Analysis* (MCDA) is such an approach (Mendoza and Martins, 2006). MCDA can be used in multi-stakeholder discussions within a company or project to derive at weighting sets and to illustrate the effects of different weighting sets.

In the WooDi project, the application of different weighting methods along with different scenarios for the future can introduce different value-systems and a way to deal with uncertainties about future world and product system development, and thereby provide a more comprehensive understanding of the implications of the assessment results. The weighting methods described above mainly deal with the environmental area and cannot account for the broad range of sustainability parameters that will have to be dealt with in the project, however, they can provide partial understanding of the potential impact. EF, for example, might be relevant to use for initial screening and as an assessment parameter in the final sustainability assessment, especially if the depletion of non-renewable resources can be integrated. To introduce also qualitative parameters and other parameters than environmental ones, MCDA can be useful. When used as a group process, it can also clarify the trade-offs and the implications of gaps in information and knowledge to the participants.

3.2. A different or broader scope of sustainability

Life Cycle Costing (LCC) is a method developed for assessing internal and external costs related to a product over its entire life cycle (Woodward, 1997). Internal costs are company costs, e.g. for research, development, planning, assets and operation and external costs are related to, e.g. environmental impacts and social effects that today are costs for society (Rebitzer and Hunkeler, 2003). An argument, other than social responsibility, for the assessment of external costs is that they tend to become more and more internalised over time as the awareness of impacts related to company activities increases, as has been the case for, e.g. today's environmental policy instruments regarding emissions, like carbon trading. Any future-oriented assessment needs to anticipate potential upcoming costs or impacts. In a review of the ways in which goal and scope are defined in LCC, it was found that most LCC studies cover only a few parts of the whole life cycle and most often at a low level of detail, i.e. a very limited type of future costs, like running costs and final waste handling or demolition costs and rarely external costs (Korpi and Ala-Risku, 2008). LCC could be useful in the WooDi project for comparing investments needed for alternative solutions in material production and to gain a greater understanding of how product cost is influenced by different impacts. The scope of the LCC could be enlarged and/or could include more details as the project proceeds and more information on the product system appears.

Social LCA is in an early stage of development compared to environmental LCA (Hunkeler, 2006; Kloepffer, 2008). Case studies are needed in order to develop the method further (Benoît et al.). A review of Social LCA studies concluded that they rely on somewhat different approaches, e.g. use either generic or site specific data and include different sets of impacts, ranging from direct impacts on workers only, like rates of injury, to broader societal consequences such as general support to developing countries (Jørgensen et al., 2008). UNEP has published a report presenting a framework for the assessment of product life cycle social impacts (Andrews et al., 2009). In this framework, social impacts are consequences of positive or negative pressures on human well-beings from an organisation's activities. The UNEP framework divides social impacts into three areas, based on what causes them: (1) social impacts caused by a specific behaviour or decision, e.g. forbidding employees to form unions or allowing child labour, (2) social impacts effected by socio-economic decisions, e.g. an investment decision to build infrastructure in a community and (3) social impacts related to human and cultural capitals, e.g. activities to improve education or health level (Andrews et al., 2009). Similar to environmental LCA, Social LCA needs a considerable amount of data input. As presently used, Social LCA mainly gathers information on organisational aspects at the enterprise or management level throughout product life cycles. In product or material development, things like location of production facilities, production volumes and customer response are often yet unknown and thereby data for several social impacts are unavailable. Social LCA, as of today, is more useful in later stages of product development when there is more information available about the product system. However, it is an advantage to be aware of what it includes throughout the whole development process so that development can be guided.

Life Cycle Sustainability Assessment (LCSA) has been suggested by e.g. CALCAS (Zamagni et al., 2009) and the UNEP/SETAC life cycle initiative (Ciroth et al., 2011) to broaden the scope of current LCA by for example combining environmental LCA, LCC and Social LCA into an integrated assessment covering the three dimensions of sustainability. Case studies are needed to develop the LCSA methodology.

SocioEcoEfficiency Analysis (SEEbalance) sets out to compare the sustainability of products and processes from a holistic perspective (Kölsch et al., 2008; Saling et al., 2005; Schmidt et al., 2004). It is a further development of the Eco-efficiency analysis, and it is developed and used by the chemicals producer BASF (Saling et al., 2002). SEEbalance includes, in addition to life cycle costs and life cycle environmental impacts, also social effects. The exact choice of sustainability indicators has a considerable effect on the result, hence results from different studies can normally not be directly compared (Lindner et al., 2010). Table 1 lists examples of sustainability indicators used in the SEEbalance method. Note that the social indicators are both positive and negative, whereas commonly used environmental impacts are negative (a higher value would indicate a higher negative impact). The developers of the SEEbalance methodology argue that a generally applicable set of indicators should be strived for to facilitate the creation of databases. However, they claim that no standard set of social indicators can be set up for the use stage of the product's life cycle since this depends on the product's specific purpose, whereas the indicators for resource acquisition, production, manufacturing and waste management can be the same for all products (Schmidt et al., 2004). It is thus necessary to consider the effects of the use stage case by case, in other words, the analyst needs to compile suitable assessment criteria and a relevant way to quantify them. Results of investigated social indicators are eventually aggregated based on two types of weighting factors: (1) the 'relevance weighting factors' which are evaluated for each analysis and reflect the examined product's influence on social issues on a national level and (2) the 'societal weighting factors' which are the same for all analyses carried out in the same country within a comparable time period and express a subjective assessment based on, e.g. public opinion polling and expert interviews on the general importance of the different social issues with regard to sustainable development (Saling et al., 2002). The same approach is used for environmental and economic indicators. The aggregated environmental, economic and social indicators for each studied alternative are normalised in relation to the least favourable result for the indicator that is set to one, and plotted in a so called SEEcube with environmental impact, costs and social impact on the three axes. Because of the uncertainties involved in the analysis, a large difference between studied alternatives is needed to obtain a significant result.

To our knowledge, no case studies are available in open literature in which SEEbalance has been used and therefore, it is not possible to review how products based on petroleum oil and wood biomass have been compared.

Table 1. Sustainability indicators suggested for SEEbalance analyses (Saling et al., 2002; Schmidt et al., 2004) and for ToSIA (Lindner et al., 2008; Lindner et al., 2010). The text has been shortened in some cases; see references for full lists.

SEEbalance environmental indicators	SEEbalance economic indicators	SEEbalance social indicators
Material consumption • Raw material usage ***Energy consumption*** • Energy usage ***Emissions to air, water and soil*** • Global warming potential • Ozone depletion potential • Photochemical ozone creation potential • Acidification potential • COD, BOD, N-tot, NH_4^+, P-tot, AOX, heavy metals, HC, SO_4^{2-}, Cl^- • Special waste	***Total costs*** • Sales price	***Employees*** • Occupational and commuting accidents • Occupational diseases • Wages and salaries • Company benefits such as subsidies • Expenditures for professional training • Strikes and lockouts ***Suppliers/business partners*** • Freedom of association • Discrimination • Forced labour • Child labour ***End customers/consumers***

SEEbalance environmental indicators	SEEbalance economic indicators	SEEbalance social indicators
• House waste • Building rubble ***Toxicity potential*** • LD_{50} ***Risk potential*** • Workplace accidents • Transportation accidents • Abuse risks • Plant safety • Fire behaviour • Land use • Noise • Quality defects		• Toxicity potential • Additional health risks (e.g. danger of accidents, addiction) • Extra benefits that enhance customer satisfaction • Completeness and quality of product information • Consumer labels (e.g. 'EU flower') ***Neighbourhood and society*** • Number of employees; unskilled workers; female managers; disabled employees; part-time workers • Company expenditures for family support • Benefits for disadvantaged people due to product quality • Violation of ethical norms due to product use or advertisement • Potential of misuse of products (e.g. as a weapon) • Potential of intensification of social and political conflicts (e.g. due to changes of traditional lifestyles) ***Future generations*** • Expenditures for R&D • Capital investment • Company expenditures for social security • Number of trainees ***International community*** • Imports from developing countries • Sum of import duties and export subsidies (protectionism) • Fair trade labels
ToSIA environmental indicators	**ToSIA economic indicators**	**ToSIA social indicators**
Total energy generation and use • Renewable • Non-renewable • Electricity from the grid ***GHG emissions & carbon stocks*** ***Generation of waste*** ***Water use*** ***Soil, water and air pollution*** ***Transport distance and freight*** ***Forest biodiversity*** ***Forest resources use***	***Gross value added*** ***Productivity*** ***Investment and R&D*** ***Total production costs*** • Raw materials from forest wood chains • Raw material from outside forest wood chains • Labour costs ***Energy costs***	***Total employment*** • Male • Female ***Total wages and salaries*** • Male • Female ***Occupational safety and health*** • Non-fatal accidents ***Education and training***

The sustainability assessment in the WooDi project aims to provide an answer to if the new diaper with wood-based absorbent material is more sustainable than today’s containing a petroleum-based absorbent material. SEEbalance aims for comparing the sustainability of two products and could be used in comparing the final WooDi product to the reference product. However, it is less useful during the WooDi product development stage when a lot of features of the product system are unknown. The SEEbalance indication of relative improvements can be used as one measure of more sustainable products (Dyllick and Hockerts, 2002). In product development, an understanding of the sustainability implications of different choices that can be made for a product system is needed, which allows for rethinking the system and innovating towards a more sustainable product. The SEEbalance tool does not presently provide any guidance on e.g. how to select parameters and how to think about the future.

The assessment method and software *Tool for Sustainability Impact Assessment* (ToSIA) was developed within the EU financed project Eforwood, specifically for sustainability impact assessment of European forestry wood chains (Eforwood, 2009; Lindner et al., 2010; Lindner et al., 2012). An example of a forestry wood chain is: stand generation, harvesting, transport, pulping, paper-making and printing. The ToSIA tool is designed to answer 'What if' questions regarding impacts on sustainable development from the European forestry wood chains. Some examples of such questions are: "How will the impact of a specific forestry wood chain on sustainable development change if the price of petroleum oil doubles?" or "...if new policies for habitat protection are introduced?". The end of Table 1 presents sustainability indicators and some sub-indicators included in the ToSIA software, as reported by Lindner et al. (Lindner et al., 2008; Lindner et al., 2010).

If needed, additional indicators can be defined and introduced into the ToSIA software. A cost-benefit analysis tool, in which all indicators' values are converted into Euros and a certain multi-criteria analysis (MCA) procedure, are available in ToSIA. In the MCA procedure proposed, a panel of stakeholders can suggest weighting factors as indicators and rank alternatives to illustrate the effect on the results of applying different value-systems.

The ToSIA methodology can be used both in the sustainability assessment of products and in comparisons of products. It is currently not possible in ToSIA to compare a wood-based value chain with a competing material chain, e.g. one based on petroleum. However, it would be possible to expand and develop further the methodology for other resource value chains. Sets of indicators developed for ToSIA could be helpful as input in developing case-relevant assessment parameters for the WooDi project. The cost-benefit analysis and MCA tools in ToSIA can be useful in aggregating and interpreting results from assessments within WooDi. ToSIA case studies have been reported, assessing for example forest management, harvesting, logging and transport processes in forest wood chains in European countries (Berg et al., 2012; Chesneau et al., 2012; Wolfslehner et al., 2012). Interesting specifics for forest management practices are described, but these are not of direct use for the purpose of this study.

4. Procedural approaches for assessing resource management

4.1. Forestry

Increased use of biological resources will likely lead to impacts on e.g. biodiversity and cultural values of land. There are systems, to be used by forest owners, that guide towards more sustainable forest management, e.g. the Forest Stewardship Council (FSC) certification (Forest Stewardship Council, 1996) and the Programme for the Endorsement of Forest Certification (PEFC) scheme (PEFC, 2010). Requirements within such systems include a broad set of aspects aimed at the sustainable management of forest resources. However, they do not take into consideration how the resources are later used in different products. These systems generally are on/off systems - you either fulfil the requirements of the system or you do not – and are thus not directly comparable to approaches like LCA or EF that, in contrast, give better/worse results on a continuous scale. The scope of this kind of system can be understood by looking for instance at the eight sustainability indicator categories suggested by the Sustainable Forest Management Laboratory (SFM, 2009): Conservation of biological diversity, Maintenance of productive capacity of forest ecosystems, Maintenance of ecosystem health and vitality, Conservation and maintenance of soil and water resources, Maintenance of forest contribution to global carbon cycles, Maintenance and enhancement of socio-economic benefits, Cultural, social and spiritual needs and values and Legal, institutional and economic framework.

FSC certification was introduced in 1993. An investigation of its progress concludes that the original intention to save tropical biodiversity through certification has failed and most certified areas are in Europe and only 10% are located in tropical countries (Rametsteiner and Simula, 2003). The certification has been very successful, however, in raising awareness and knowledge levels regarding sustainable forest management. As continuous improvement is built in to the certification system, forest management is continuously improved in each certified area. The management systems do not, however, guarantee sustainable forest management, but work in the direction of more sustainable forest management.

FSC certification and PEFC are both international systems and both systems allow for some adaptation to national conditions in consultation with different stakeholders. This is carried out differently in the two systems; FSC is centralised and based on international indicators while PEFC is decentralised and based on regional guidelines. This means that FSC is more similar around the world than PEFC. On the other hand, PEFC is, due to its regional adaptation, more flexible and can address local issues, like particular plants and animals due to special geographical conditions. FSC certification is adapted to national and sub-national indicators in each country via negotiations with different stakeholders like state agencies, forest owners, non-governmental organisations and different types of local communities. FSC certifications can therefore take into consideration national matters such as specific laws or native people's cultures. However, even though forests are highly diverse around the globe, FSC certifications do not include considerations of variations in local geographical conditions. PEFC also applies a multi-stakeholder approach and therefore varies between regions, sometimes also within counties; PEFC criteria are, for example, different for the north and the south of Sweden. Since both FSC and PEFC take into account the different interests of several stakeholders, trade-offs between different interests are necessary. Originally the PEFC system had its main focus on small-scale forestry owners while the FSC system focused on large-scale owners, but today it is possible to hold an FSC/PEFC dual certification.

For both FSC certification and PEFC in Sweden, at least 5% of the land area used for forestry should be set aside for biodiversity protection. In practice, this generally translates into the 12% earlier discussed, regarding EF and the Brundtland commission recommendation, after the addition of other land that should be set aside, according to the certification schemes, such as border zones alongside roads and lakes to avoid erosion and to secure water quality when harvesting. Neither of the certification schemes have systems for handling local variations potentially of great importance for biodiversity on a local level, like snags of different species and the number of windfalls that should be left.

It has been suggested that aesthetic values should be included in the assessment of the utilisation of forest resources (Panagopoulos, 2009). This would require new forest management standards and a way to estimate the public opinion of forest aesthetic values.

For the WooDi project, the share of the forest area that is certified by FSC and/or PEFC could be used as an assessment parameter indicating an acceptable level of resource management, including, e.g. responsibility for biodiversity, at least until more detailed indicators can be developed.

4.2. Petroleum oil extraction

Regarding petroleum oil extraction, no sustainable management systems comparable to the forest management systems have been found. There are some recommendations from the Energy and Biodiversity Initiative, consisting of leading conservation organisations and energy companies, that point to issues similar to those in the forest management systems, e.g. to include the conservation of biodiversity in strategies for petroleum and gas exploration and processing (EBI, 2003). As for all other sectors, there are Quality Management Systems, such as the ISO 9001:2008, that can be applied to petroleum oil extraction. There are also different technical standards for certain activities and products and fuel standards (ASTM, 2009), but no standard with the main aim of resulting in long-term sustainable petroleum extraction and management.

4.3. Biofuels

Biofuels are not of direct interest in the WooDi project since what is studied is a wood-based material that is to be used in the absorbent core of an incontinence diaper. However, management systems for other products that are bio-based and that compete with non-renewable materials might provide valuable information on important considerations in the comparison, especially if they include an attempt to compare the use of wood and petroleum.

With the increasing interest in biofuels, certification schemes have been discussed. In 2006, Smeets et al. suggested a certification system for sustainable ethanol production, recommending that e.g. soil quality, erosion prevention, biodiversity preservation, reforestation, local food security and land use competition should be considered (Smeets et al., 2006). The Roundtable on Sustainable Biofuels (RSB) is an international initiative involving farmers, companies, non-governmental organisations, experts, governments and inter-governmental agencies. In 2008, the RSB released its first draft of a generic standard for sustainable biofuels production (RSB, 2008). The RSB standard includes requirements for areas similar to the criteria suggested by Smeets et al. The draft is a starting point for greater awareness and enables a move towards more sustainable production and was not developed to compare biofuels but rather to give credibility to the biofuel producer.

In 2008, an analysis was presented of 20 different certification systems for biofuels from agricultural and forestry products. In the study, Fehrenbach and co-workers concluded that environmental indicators like energy balance, GHG emissions in the biofuel production chain and waste management were only rarely dealt with and that competition for land area, food safety and usage of the products were not addressed at all in any of the 20 certification systems (Fehrenbach et al., 2008). A number of the aspects that where included, like the conservation of biodiversity, still lacked measurable indicators. The UNEP Resource Panel reports similarly on the global situation of assessing biofuels, and also highlights the importance of including not only global warming but also eutrophication and acidification in comparative assessments of biofuels from energy crops and fossil fuels (Bringezu et al., 2009a). A similar conclusion, that generally very few environmental impacts are actually assessed, is also reported in a review of 47 life cycle based studies comparing bio-ethanol systems to conventional fuel; generally only GHGs and net energy were considered (von Blottnitz and Curran, 2007).

A review of accounting approaches for quantifying GHG emissions relating to direct land use change and indirect land use change from biomass has been reported (Fritsche et al., 2010). The review focuses on discussions on options for reducing indirect land use change and recommendations for inclusion of land use change in bioenergy and biofuel policies. The EU directive on renewable energy of 2009 includes guidelines for how to calculate impacts of GHG emissions of biofuels and points out biodiversity as an important factor to consider (European Commission, 2009b).

In terms of biodiversity protection, a risk minimisation strategy in biomass use has been suggested in a strategy for certification of biomass in international trade (U. R. Fritsche et al., 2010). The strategy addresses three core issues 1) Conservation of land with a significant biodiversity value, 2) Minimizing negative effects from indirect land use change and 3) Agricultural practices with low negative effects on biodiversity.

In a study of ranking sustainability criteria for bioenergy systems, experts expressed a concern on the lack of holistic view in the sustainability assessment framework i.e. a lack of understanding of how the parameters together build a relevant parameter set that answers the question at hand (Buchholz et al., 2009). To create such a holistic overview, Buchholz suggested using participatory exercises, i.e. including various stakeholders' voices and values, such as the earlier described MCDA method, since that has proven useful on complex issues in fields related to bioenergy.

For the WooDi project, the described systems provide examples of areas to include and indicators and methods that can be applied, however, the lack of measurable indicators within some important areas will have to be dealt with.

5 Case studies - comparisons of products derived from petroleum and biomass

5.1 Agrofuel and petrofuel

A large part of the scientific discussion on fossil versus biological resources has, so far, been focused on future fuels for transportation. There is vast literature on assessment of agrofuels and other first-generation biofuels, including comparisons with petrofuels. Most such studies have focused on the assessment of GHG emissions, often referred to as the CF. Examples of recent such studies have been reported by Edwards et al. in 2007, by Johnson and Heinen in 2008 and by Gnansounou et al. in 2009 (Edwards et al., 2007; Gnansounou et al., 2009; Johnson and Heinen, 2008). More seldom such studies include comparisons of effects on e.g. ecosystem quality, employment and economy. Dominguez-Faus et al., for example, point out that the effect on water security is seldom included and suggest the use of WF in the evaluation of biofuels (Dominguez-Faus et al., 2009).

The EF was used to assess different biofuels in a study reported by Stoeglehner and Narodoslawsky in 2009 (Stoeglehner and Narodoslawsky, 2009). The study concludes that EF analyses can be used to identify trends in land use demand for different scenarios. This information can then be used as a basis for further discussion about dedicating land to biofuels and other products.

It has been shown by the International Institute for Applied Systems Analysis, on behalf of the OPEC Fund for International Development, that national policies that strive towards increasing agrofuel production capacity can conflict with goals regarding food security (OFID, 2008). The same study concludes that agrofuels only contribute to modest increases in agricultural value in developing countries and also create additional risks of deforestation and other threats to biodiversity. Others acknowledge that improvements are needed in policies and technology in order to meet global demands for both food and biofuel feedstocks (McNeely et al., 2009; Tilman et al., 2009). The same argumentation should be applicable to an increase in the overall use of biomaterials in society, which could be one of the results of turning to wood-based diapers.

5.2 Diapers

Earlier assessments of diapers are of particular interest for the WooDi project. Life cycle environmental impacts of different types of diapers have been investigated in several studies (Aumonier and Collins, 2005; Edana, 2008; Hakala et al., 1997; Immink, 1999; Svensson, 1994; Wijkmark, 2004), but no studies have been found with the specific goal of comparing the use of materials with different resource bases in the diapers. The studies compare different brands and types of disposable and reusable diapers and have different scopes. In none of the studies is one alternative clearly superior or inferior to the others in terms of their environmental performance. The life cycle stages that give the largest impacts differ between different diaper types.

In an LCA study of disposable diapers, home laundered flat cloth diapers and commercially laundered prefolded cloth diapers delivered to the home, commissioned by the UK Environmental Agency in 2009 non-renewable resource depletion, acidification and climate impacts were the most significant categories when normalised to total European impacts (Aumonier and Collins, 2005). The assessment also considered ozone depletion, photo-oxidant formation, eutrophication, human toxicity and aquatic and terrestrial toxicity, but did not include impacts such as land use and impacts on biodiversity by each system. Impacts from waste management did not contribute substantially to the overall totals for any of the systems, although the proportion contributed by waste management not surprisingly is greater for the disposable diaper system than for the two reusable diaper systems. The results suggest that the focus for improving the environmental performance of disposable diapers should be on improvements in materials manufacturing and weight reduction and for reusable diapers, on reducing energy consumed during washing and drying. For the WooDi project, this suggests that apart from changing to a renewable material base, it is important to achieve a resource efficient material production stage as well as ensure that material function is not deteriorated to avoid the need for more material.

6. Overview of results and future outlook

That a material is "bio-based" is sometimes seen as a sustainability attribute in itself, but in a world with increasing competition for biomass resources, "bio-based" will not be enough. To include the scope of considerations that a holistic sustainability perspective requires, assessment parameters for many different areas should be used. However, in order to make the work load manageable, a selection that reflects the most important sustainability considerations for a specific case has to be made. The selection of assessment parameters and the weighting factors applied in later stages of the assessment should reflect the potential significant influence on sustainable development of the specific product systems at hand. In literature, a number of aspects to be evaluated in a sustainability assessment are proposed, both regarding environmental, social and economic matters. In Table 2, ten example areas are listed for which different sustainability parameters have been suggested, together with examples of how these can be expressed. The areas in Table 2 were selected because they have a clear connection to the comparison that is in focus in this study between the use of petroleum and renewable wood as the material base for products. However, other aspects than those listed may prove to be relevant and Table 2 should be seen as an illustration of suggestions from available literature rather than a recommendation.

Table 2. Ten different areas potentially important to include in a sustainability comparison between the use of petroleum- and wood-based materials in products. These areas have been suggested or used in different assessments in literature.

Sustainability aspect		Examples of assessment parameters for the aspect	Examples of methods or initiatives that include the aspect	Examples of studies in literature that present or suggest the aspect, but do not use it	Examples of product assessments in literature that use this aspect
Environmental	**Depletion of non-renewable petroleum resources***	Petroleum usage (m^3)	LCA, Eco-efficiency, SEEbalance, ToSIA	(Andersson et al., 1998; Aumonier and Collins, 2005; Baumann and Tillman, 2004; Edana, 2008; Gnansounou et al., 2009; Hakala et al., 1997; Helming et al., 2008; Immink, 1999; Lindner et al., 2010; Svensson, 1994; Tufvesson and Börjesson, 2008; Walter and Stützel, 2009, 2009b; Wijkmark, 2004)	(Andersson et al., 1998; Aumonier and Collins, 2005; Gnansounou et al., 2009; Hakala et al., 1997; Immink, 1999; Svensson, 1994; Tufvesson and Börjesson, 2008)
	Occupation of land area	Land area usage (hectare)	Ecological footprint, LCA, Eco-efficiency, SEEbalance	(Banse et al., 2008; Baumann and Tillman, 2004; Berndes et al., 2003; Gaia Foundation et al., 2008; Graymore et al., 2008; Helming et al., 2008; Holmberg et al., 1999; Mathews, 2007; Nguyen and Yamamoto, 2007; OFID, 2008; Rathmann et al., 2010; Stoeglehner and Narodoslawsky, 2009; Wackernagel and Yount, 1998, 2000; Walter and Stützel, 2009, 2009b)	(Nguyen and Yamamoto, 2007; Stoeglehner and Narodoslawsky, 2009)
	Emissions to air of greenhouse gases	Global warming potential (kg CO_2 eq.)	LCA, Carbon footprint, ToSIA, Eco-efficiency, SEEbalance	(Aumonier and Collins, 2005; Baumann and Tillman, 2004; Fehrenbach et al., 2008; Gnansounou et al., 2008a; Gnansounou et al., 2009; Helming et al., 2008; Johnson and Heinen, 2008; PAS 2050, 2008; RSB, 2008; Walter and Stützel, 2009, 2009b)	(Aumonier and Collins, 2005; Gnansounou et al., 2008a; Gnansounou et al., 2009; Johnson and Heinen, 2008)
	Emissions to air (other than greenhouse gases), water and soil	Acidification potential (kg SO_x eq.), Photochemical ozone creation potential (kg ethene eq.), Eutrophication potential (kg PO_4^{3-} eq.)	LCA, RSB**, ToSIA, Eco-efficiency, SEEbalance	(Baumann and Tillman, 2004; Helming et al., 2008; RSB, 2008; Walter and Stützel, 2009, 2009b)	(Mattsson et al., 2000)
	Impact on biodiversity	Number of species per m^2, Population of each species per m^2.	Forest certifications, RSB**, some specific LCAs, ToSIA	(Aumonier and Collins, 2005; Baumann and Tillman, 2004; Berndes et al., 2003; EBI, 2003; Fehrenbach et al., 2008; Garraín et al., 2007; Helming et al., 2008; MEA, 2005; OFID, 2008; RSB, 2008)	(Mattsson et al., 2000)

Sustainability aspect		Examples of assessment parameters for the aspect	Examples of methods or initiatives that include the aspect	Examples of studies in literature that present or suggest the aspect, but do not use it	Examples of product assessments in literature that use this aspect
Economic	**Operating costs**	Cost of raw material, Cost of energy, Cost of labour	LCC, ToSIA, SEEbalance, Eco-efficency	(Forest Stewardship Council, 1996; Lindner et al., 2010; PEFC, 2010; Saling et al., 2002; SFM, 2009)	Not found
	Assets needed	Capital investment, Investment in research, development, increased capacity and use of new and improved technologies	LCC, ToSIA, SEEbalance, Eco-efficency	(Schmidt et al., 2004; SFM, 2009)	Not found
Social	**Impacts on health or safety**	Number of sick days, Number of severe accidents	ISO 9001, Eco-efficiency, Social LCA, SEEbalance, ToSIA	(Hunkeler, 2006; Walter and Stützel, 2009, 2009b)	Not found
	Impacts on surrounding communities, culture and recreation	Respect for existing water rights, Opportunities for employment, training and other services, Participation of women, Poverty alleviation in specific regions	Forest certifications, RSB**, SEEbalance	(Baumann and Tillman, 2004; Fehrenbach et al., 2008; Forest Stewardship Council, 1996; Gaia Foundation et al., 2008; OFID, 2008; RSB, 2008; Steen, 1999; Walter and Stützel, 2009, 2009b)	Not found
	Adherence to social rights	Equal remuneration for work of equal value, Protection of the right to organise	Forest certifications, RSB**, Social LCA, SEEbalance	(Fehrenbach et al., 2008; Forest Stewardship Council, 1996; Hunkeler, 2006; RSB, 2008)	Not found

* could alternatively be seen as an economic or even a social aspect

** *RSB* – Roundtable on Sustainable Biofuels

Table 2 also shows that while a lot of sustainability assessment parameters are discussed in literature, only a few, predominantly environmentally related ones, have so far been in actual use in case studies. One important reason for the present lack of assessment parameters is the difficulty in formulating assessable indicators that describe social interactions and impacts on ecosystem services such as biodiversity.

There is a need for methods that can assess and compare the depletion of petroleum resources and limitations in terms of land area, and other aspects that relate to the management of land, within the same comprehensive framework. Assessment parameters that describe these and other resource limitations are needed.

A sustainability assessment has to be based on a case-specific interpretation of important sustainability considerations and this has to be translated into a set of assessment parameters. Parameters then have to be assessed and aggregated into a holistic understanding of the sustainability performance, with opportunities to compare the sustainability profile of different products, also when the sustainability profiles peak in completely different areas. In the WooDi project, there is thus a need for a description of what is meant by sustainability, and a comprehensive set of parameters that cover the most important sustainability considerations. Many different sources of knowledge will have to be consulted, such as literature and different stakeholders in the value chain. Furthermore, a somewhat iterative approach is needed since some assessment parameters will have to be assessed in a preliminary screening before their potential relative importance can be understood.

Table 3 contains a summary of elements, found in different methods described in literature, which can be of use in the product sustainability assessment throughout the material development process in the WooDi project. The analytical approaches for assessing and comparing product sustainability are often not intended to cover the full range of potentially important sustainability aspects; they typically focus on selected aspects, e.g. on the CF (GHG emissions) of products and activities. The procedural approaches commonly contain targets or criteria that represent an acceptable level or outcome for each parameter. Most certification systems, e.g. FSC certification, only consider the management of the resources but do not consider the use of the product and how it is produced and therefore do not have a life cycle perspective. However, requirements within such systems often include a broad set of sustainability aspects.

Table 3. Overview of how elements of different methods can be of use in the sustainability assessment in the WooDi project

Method/approach/system	Description/Impact considered	To keep in mind	Usefulness for WooDi project
Life Cycle Assessment (LCA) in general	Environmental impacts over the entire life cycle	• Only environmental performance • Different weighting methods emphasise different concerns • Different LCA studies are not comparable due to different goal and scope	• LCA methodology can be useful in the sustainability assessment • Common impact categories can be used as a basis for selection of case relevant environmental assessment parameters • Case studies provide understanding of dominant parameters and activities
Carbon Footprint (CF)	GHG emissions (climate change) over the entire life cycle	• Indirect land use not included	• As one of the sustainability aspects in a sustainability assessment

Method/approach/system	Description/Impact considered	To keep in mind	Usefulness for WooDi project
Water Footprint (WF)	Fresh water used, directly or indirectly, to produce a product (scope is generally cradle-to-gate)	• Water in the product's use stage is generally not included in the WF of the product, but in the WF of the consumer using the product	• As one of the sustainability aspects in a sustainability assessment
Material Input Per Service unit (MIPS)	Amount of resource input (resource consumption) over the entire life cycle	• Unspecific to particular materials as well as substance specific hazards	• As a rough estimate of resource use • As one of the assessment parameters in a sustainability assessment
Ecological Footprint (EF)	Estimate of land area, directly and indirectly, over the entire life cycle	• At present, methods for translating consumption of non-renewable resources into EF are lacking	• As an initial screening • As one of the assessment parameters in a sustainability assessment
Life Cycle Costing (LCC)	Internal and external costs over the entire life cycle	• As most often used, LCC only includes a very limited type of future costs and rarely external costs. For a sustainability assessment, more complete types of LCC should be employed	• To estimate investments needed for alternative solutions to material development • As one of the sustainability aspects in a sustainability assessment
Social LCA	Social impacts over the entire life cycle	• The scope varies from impacts on workers only to broader societal consequences like support to developing countries	• To give awareness of what social impacts that may arise during the whole development process so that development can be guided, however, in early product development, when many features of the product system are unknown, a focus on the use and production stages is suitable
SEEbalance	Comparing sustainability of products and processes over the entire life cycle	• Assesses, as presently set up, the relative impacts, comparing two or several product alternatives and therefore provides only limited input on potential improvements	• As inspiration when defining case relevant social, environmental and economic parameters • For comparing the sustainability of the products in the final assessment; requires that the parameters and the weighting method have been adapted to the case
ToSIA - A Tool for Sustainability Impact Assessment of Forestry-Wood Chains	Sustainability assessment software, developed for European forestry wood chains	• Case-relevant sustainability parameters for the diapers need to be defined and if necessary introduced	• As inspiration when defining case relevant parameters for the forestry wood chain • As a software tool for managing the WooDi

Method/approach/system	Description/Impact considered	To keep in mind	Usefulness for WooDi project
		into the system	sustainability assessment
Forest certifications	FSC and PEFC certification are based on compliance to performance standards	• Consider the management of resources but not the use of the product and how it is produced, i.e. do not have a life cycle perspective	• As a control parameter, e.g. compliance with FSC certification or not
Petroleum oil certifications and standards	Certifications and standards for quality management like ISO 9001:2000 and CEN/TC 12	• Developed to aid in compliance to laws and to facilitate exchange of equipment, not for moving towards sustainability	• As a control parameter, e.g. for compliance with laws

The SEEbalance and ToSIA methods include environmental, economic and social parameters. Both include lists of parameters that might be useful in product assessments, however, none of the approaches advice in the selection of parameters to reflect important and relevant sustainability considerations for a specific case. In fact, the seemingly well thought-through lists may even trick analysts into thinking that a generic list is suitable for every system. Using the same parameter list facilitates comparison between different studies and may be relevant in some situations. For the WooDi project, however, the development of the new material is to be guided towards a more sustainable diaper product and such a process must be informed using a parameter set that reflects the specific definition of what a sustainable product implies in the specific case.

In the SEEbalance scheme, the weighting is intended to be performed by experts and the SEEbalance practitioner while the ToSIA scheme stresses and encourages the involvement of different stakeholders in the weighting procedure. In the built-in MCA tool, different stakeholders can propose a weighting factor to each indicator, to rank alternatives. The range of results of the different weighting proposals is also visualised to the stakeholders. ToSIA results will probably be more understandable to people that have been included in the process and can thereby provide better guidance to these people in their work. The result of the sustainability comparison in SEEbalance, the SEEcube, is intended for decision-makers that have not been involved in the process and is designed to be easy to grasp but not to provide any details on the background or limitations of the results. The method is not constructed with the aim to guide project team members throughout a product development process.

It is clear that available methods contain many useful elements and approaches, as can be seen in Table 3. For the needs of the WooDi project there are two important gaps: there is a lack of parameters describing potentially important sustainability considerations in a comparison of the use of wood or petroleum as raw material and there is a need for an approach that establishes case relevant sustainability assessment parameter sets. To fill the gaps noted in this screening of methods, an approach for establishing case relevant product sustainability assessment parameter sets should be developed.

7. Conclusions

This review was performed based on the need of a method for selecting and assessing a set of parameters for comparing the sustainability of incontinence diapers produced with either petroleum-based or wood-based materials. The review was made based on the presumption that such a set of assessment parameters, as well as their relative weights, must be developed based on the circumstances of the specific case.

The review revealed that a diverse number of approaches and methods exist that can assess different attributes or articulations of product sustainability for parts of or whole product life cycles. Numerous sustainability assessment parameters, mainly for environmental aspects, have been used or suggested. Almost all reviewed assessment approaches use premade lists of assessment parameters but without advice on how to adjust them towards a more case-relevant set of parameters.

Parameters are lacking in some areas, and also knowledge of how to describe these missing parameters. This is, for example, the case for social progress, and impacts on biodiversity and other ecosystem services.

In moving towards a bio-based society, comparisons between use of different types of resources faced with different types of restrictions will be increasingly important. In available literature, no ready-to-use methods for comparing use of different types of limited resources, like petroleum, land area and water (as in a comparison between petroleum-based and wood-based materials), have been found.

Finally, approaches are lacking for establishing case specific weighting of parameters, which is necessary for handling case specific trade-offs.

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Paper II

Insights from guiding material development towards more sustainable products

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Abstract

Faced with current challenges in society, many companies will need to develop more sustainable products in order to continue operations in the long term. Therefore, ways of identifying important sustainability considerations in the early stages of material or product development are of importance. This article provides suggestions on how material and product development projects can be guided towards more sustainable products. The suggestions have been derived from action research carried out in an industry/university joint material development project. The article provides a description of sustainability assessment activities that were performed in the project in order to guide development towards more sustainable products, reflections on the experience leaned from this project, and suggestions for similar projects in the form of an overall process based on team learning with the aim of guiding material development towards more sustainable products. The suggested process emphasizes the material or product development team's need to understand which surrounding world and future-oriented considerations will have significant impacts on the specific product's sustainability performance. A specific need to focus on establishing relevant sets of parameters that can be translated and integrated into each team member's everyday work tasks has been identified as important for a successful project and is emphasized in the suggested approach.

Keywords

Action research, team learning, sustainability assessment, early product development

Introduction

In order to stay in business in the long term, companies need to develop and offer more sustainable products. Achieving this involves many different considerations, such as impacts on the resource base, on climate, and other challenging aspects of human society. The product development task is already very complex and involves global market issues like customer preferences and other stakeholder interests, patents, policy instruments, and limitations represented by supply chains, such as distances to suppliers and the availability of materials. Integrating these new perspectives makes the task even more complex.

This article introduces an approach for guiding material development towards more sustainable products. The approach has been developed as a response to the needs of a specific project but it is here described in a generalized way along with some activities performed in the project with the hope that it can provide useful input to other similar projects. The suggested approach is the outcome of using action research within an industry/university joint material development project. The project aimed at developing wood-based materials to replace petroleum-based materials in products. The goal was that a product containing the new materials would be more sustainable than the present one.

Manufacturers of currently used petroleum-based materials have over a long period of time successfully worked on the environmental optimization of their processes and on the improvement of material properties. To develop a new material that performs better than the material to be replaced, taking into consideration all relevant sustainability aspects, is therefore expected to be a difficult task. However, improved performance in areas other than the environmental parameters that are conventionally measured may present compensatory effects that outweigh, for example, a slight increase in acidification or energy use. But, in order for this change in effects to be considered, assessment methods capable of handling a view that is more holistic than the current one will have to be in place. Furthermore, an approach is needed that guides the material development team to greater awareness of such sustainability considerations in order to achieve more than just an optimization of the current situation and to a rethink based on a more holistic view.

The methods that have been employed in sustainability assessment activities in the project build on insights gained and elements identified in a review of existing sustainability impact assessment tools that were reported elsewhere (Clancy et al. 2013). That review focused, in particular, on opportunities for comparing the sustainability of the use of wood- and petroleum-based materials in products and it showed that available tools do not fulfill the requirements of handling this comparison, because of their present inability to deal with some potentially important aspects. Such aspects include social impacts, impacts on ecosystem services and biodiversity, and competition for different types of limited resources like petroleum, land area and water.

The results from the preceding study also reinforce the understanding that in a sustainability assessment aimed at guiding product development a life cycle perspective is necessary, essential sustainability considerations must be developed and described from case to case, and assessment parameters need to be selected in relation to such a description. The study also reveals that the description should not only address present sustainability concerns but also possible future concerns. Consequently, a specific challenge in product development emerges; since the product system is not yet fully defined, a process that iteratively develops knowledge in three mutually dependent areas is needed. These three areas are: the design of the product system, the corresponding relevant sustainability assessment parameters, and the resulting sustainability performance, as illustrated in Figure 1. These points of departure are sometimes implicit in projects that aim at assessing product sustainability in the early product development stage but are seldom clearly stated and, therefore, often forgotten. This complexity is one reason the importance of team learning in guiding product development has been identified by several authors (Edmondson & Nembhard 2009, Hardi & Zdan 1997, ISO/TR 14062 2002). In the present article, team learning refers to the process of working collectively in a group to achieve common objectives by acquiring, sharing and combining knowledge through working together, as discussed in further detail regarding effective team learning in organizations by Decuyper et al. in 2010.

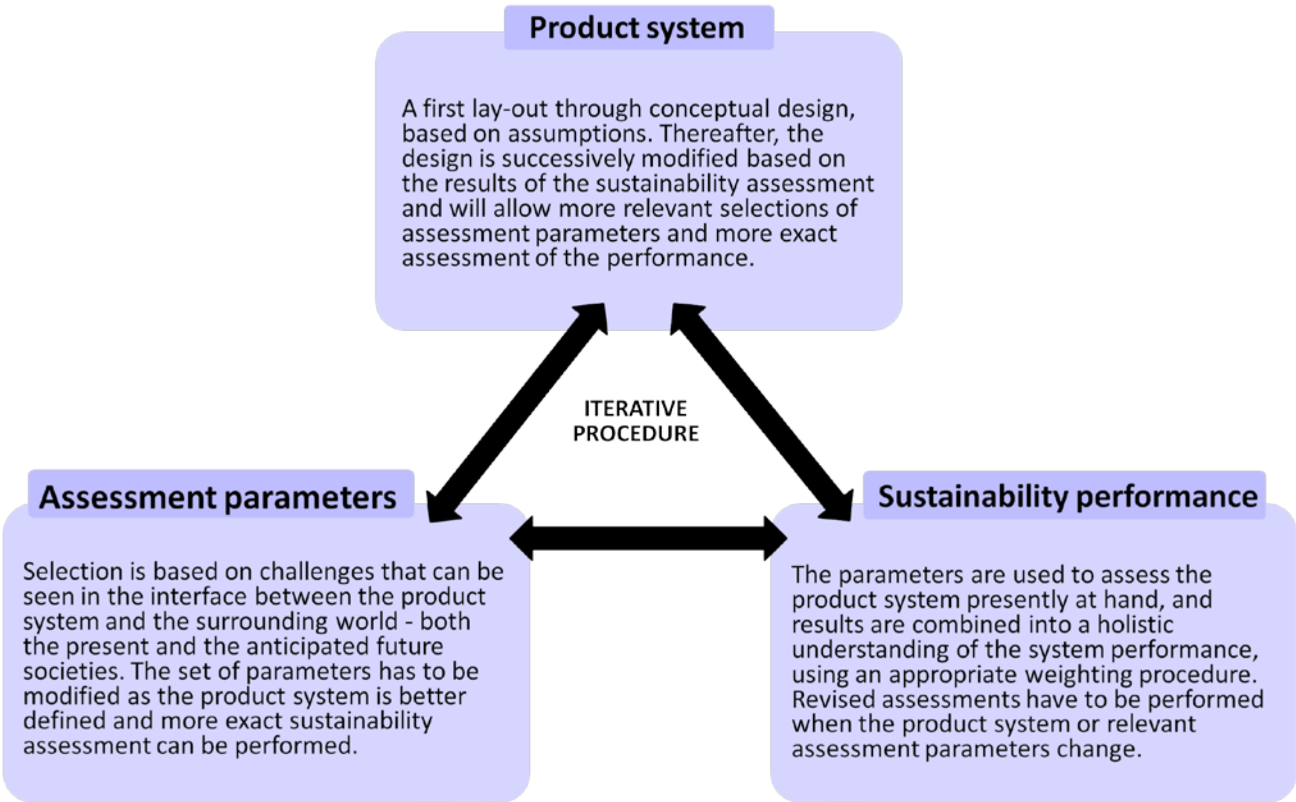

Figure 1. Illustration of the iterative procedure advocated in outlining the product system, in selecting relevant assessment parameters for the system and in assessing the sustainability impact of the product

A number of concepts and tools, like Ecodesign, Cleaner Production and Life Cycle Assessment (LCA) have been developed to make it possible to integrate environmental or sustainability aspects into different stages of product development (Karlsson & Luttropp 2006). These are generally constructed in such a way that they result in the environmental improvement of existing products and, consequently, they may result primarily in the optimization of the current product system, e.g., by replacing product parts or processes representing major environmental impacts based on the industrial processes currently in use. Such approaches normally result in marginal improvements when compared with the present situation. Since a more sustainable future society may put very different demands on products than even the strictest environmental requirements of today, sustainable product development should be more future-oriented, i.e., based on a vision of the long-term sustainability of society and on an understanding of what challenges this poses to the product system under development. This difference in focus, on either optimization or future-orientation, has been discussed by Van Weenen in relation to sustainable product development (Van Weenen 1997). Van Weenen concludes that future-orientation requires that the project team applies both a holistic perspective and a life cycle perspective in their considerations.

Several suggested approaches for integrating future-orientation into product development are based on applying the four principles for sustainability developed by Robèrt and Holmberg (Holmberg 1998) in a backcasting procedure in strategic planning towards sustainability (Holmberg & Robèrt 2000):

a) Defining criteria for sustainability
b) Describing the current situation in relation to the criteria for sustainability
c) Envisaging future sustainable solutions
d) Finding strategies towards the solutions

One such approach aims to develop and test the robustness of a business idea (Lundqvist et al. 2006), but its use in product development has not been described. Another approach has taken this one step further and has developed guiding questions to promote a holistic perspective in product development (Byggeth et al. 2007). As a complement to the guiding questions, and to provide an overview of major sustainability challenges and opportunities early on for management and for the product development team, templates for sustainable product development have been proposed (Ny et al. 2008). Both of these two later approaches require a facilitator to develop and/or choose the guiding questions since the product development team members themselves do not have the requisite knowledge. Consequently, the desired understanding needed for the material or product developers to continue making informed decisions for more sustainable products can probably not be achieved.

To develop new materials is in itself a complex task. To both realize and take into account which steps that can lead towards a product that is sustainable in the long term is even more challenging. Since decisions made in early product development strongly affect the sustainability performance of the finished product, this can hardly be done effectively by anyone other than the material developers themselves. To end up with more than just marginal improvements in the current situation requires that the whole team is supported in developing an understanding of important sustainability concerns (present and future) in the same way that they take into consideration other performance criteria for the product. Since no approaches have been found in literature that are intended to guide a process of product development through these different concerns, this paper suggests a team-learning approach that has emerged from experiences of action research in a material development project in which the goal has been to make it possible to produce more sustainable products.

In the following section, the research methodology is presented and then sustainability assessment activities conducted in the project are described. Thereafter, reflections on experiences from the activities are given as four lessons learned. Finally, a suggested process for guiding material development towards more sustainable products is described.

Research method

In the suggested process, the "team" is defined as the group of people put together to develop the material or product and the sustainability assessor is part of the team. The "sustainability assessor" facilitates the team process, searches for, compiles and presents the information the assessment can be based on and decides when to move on.

The action research and the suggested process will here be described from the sustainability assessor's perspective. The action research was carried out during the first two years of sustainability assessment activities in a four-year material development project. The project was a collaboration between two companies and two university research groups. Both companies involved had a long tradition of working with environmental improvements and the safety of their products.

Action research means that the researcher tries to change or improve something in an ongoing project (in this case in guiding product development towards sustainability) and at the same time observes the process and its outcome. Action research involves utilizing a systematic cyclical method of planning, taking action, observing, evaluating (including self-evaluation) and critical reflection prior to planning the next cycle (Wadsworth 1998).

Each sustainability assessment activity was thoroughly planned, participants' reactions during the exercises were observed and the assessor's own experiences were noted, and the results were reflected on before subsequent exercises were designed. Different forms of feedback were generally requested directly after the activity, and sometimes spontaneous feedback was directly or indirectly achieved, either in connection to the activity or later on.

Description of sustainability assessment activities

This section provides an overview of the main sustainability assessment activities that were performed in the project in order to guide material development towards more sustainable products by using a team-learning approach.

A. Setting the focus on the goal and on collaboration

A kick-off meeting and an introductory course early on in the project involved discussions about collaboration, knowledge exchange, the project goal, the product under study and its main properties, the production process, and sustainable development. This created the sense of a shared goal and a joint mission, however, what sustainability means in practice for the specific material development project and how it may affect development in the project was not discussed in detail at the time.

B. Exploring the challenges of sustainability assessment

A multi-criteria analysis group exercise was carried out with the project team after only a few months in order to provide an understanding of the general principles of the sustainability assessment at an early stage and the issues that may arise. All groups ended up with a favorable result for the new product, indicating a common belief in the project idea. This exercise gave the team insight into how an assessment can be performed, what can be included in the assessment, what the uncertainties and difficulties are, and that the assessment is inevitably based on values and strongly dependent on the existing level of knowledge about potential impacts. The aspects that were selected by the different groups were similar and rather unspecific, including resources, waste, money and social aspects.

C. Describing sustainability and current unsustainabilities and developing visions of possible long-term solutions

In a series of workshops, the sustainability concept was explored in order to provide meaning to the specific material development project; these activities were inspired by the backcasting approaches mentioned earlier. A discussion of what a sustainable society implies, in specific in relation to the considered target, was held and the consensus view that emerged was documented as a mind map. In order to check that important areas had been included, the content of the mind map was discussed in relation to the four principles of sustainability (Holmberg 1998). Each company then performed and presented a present state analysis of how different aspects of sustainability are violated today, throughout the value chain, focusing also on opportunities for the company to influence the situation. Finally, a brainstorming activity was performed in order to identify long-term solutions for the product that fulfill the agreed upon sustainability criteria. This activity made the team envision sustainable long-term solutions for the product function that go beyond the goal of the project in order to provide an understanding for what types of development in the project that may truly lead towards sustainability.

D. Illustrating the environmental challenge of the task

Results and conclusions of early cradle-to-gate LCA estimates of the new material were shown and discussed to enhance the understanding of the product system and the challenges in terms of different environmental parameters (Clancy et al. 2010). The estimates showed that the presumed additional use of chemicals and energy for the new material may provide challenges in a comparison with presently used materials that have been technically and environmentally optimized over a long period of time. The estimates also showed that the minimization of energy demand, in particular, is an important task in the project for reaching the goal of more sustainable products.

E. Illustrating the challenges of increased use of renewable resources

To enhance the understanding of possible long-term effects of increased wood resource use, an estimate of the wood resource use, if the new products were produced in large scale for the European market, was made and recalculated into how much forest area this could potentially occupy (Clancy et al. 2010). A projection was also made to 2050. This exercise not only illustrated potential challenges of increased wood resource use but also illustrated the importance of considering both potential market shares and future societal development, and also highlighted methodological issues in terms of how increased fiber use can be translated into occupied land area.

F. Listing available sustainability parameters

An inventory of about 500 sustainability assessment parameters available in literature was compiled, both to provide a list to select useful parameters from and to find where the major gaps were in terms of the availability of parameters to cover the full range of potentially relevant sustainability aspects. The inventory reinforced the understanding that we cannot rely on existing methods and ready-made sets of parameters, since there are severe gaps, particularly in, for the project, important areas such as land use and comparisons between renewable and non-renewable resources. Discussing the list in relation to the earlier discussion on the meaning of sustainability for the specific project illustrated these gaps to the project team.

G. Discussing the importance and the usefulness of different sustainability parameters

Selected sustainability aspects of relevance for the product were presented to the team by the assessor and each aspect's importance to the project was discussed. Examples of aspects that were intensely discussed are land occupation, the depletion of non-renewable resources, customer satisfaction with product function, competence development of co-workers, assets needed, e.g., the machinery to produce the new material, and working in a transparent way with stakeholders. For aspects that were deemed essential, assessable parameters were discussed. The exercise aimed at providing an understanding to the team of the different aspects and parameters that may be involved, and illustrated that there are many different ways to assess sustainability.

H. Connecting the work of developers to properties of the product and to sustainability aspects

When developing a material, it is important to understand which specific material properties are needed in order to deliver the desired product function, and how these affect the sustainability performance in different product life cycle stages. A workshop was performed with the aim of identifying the material properties (the material developer works at this level) with the strongest connection to the product function (the customer experiences the product at this level) and to different sustainability considerations (this is the level that the assessor operates on). The workshop focused on describing customer needs and sustainability aspects of the product and connecting these needs or aspects to material properties that the material developers work with in their daily activities. This was intended to give more clarity to the material developers about the properties to be improved and the reasons why.

I. Increasing the understanding of the dependence on world development

To increase the understanding, in the team, of how developments in the world can affect the sustainability of a product, a scenario analysis was performed following the description by Lundqvist et al. (Lundqvist et al. 2006). External factors which may influence the final product were identified in a brainstorming activity. The identified factors were discussed and placed in a diagram based on their predictability (x axis) and on their potential impact on the sustainability of the final product (y axis). Two highly unpredictable and highly impacting, but unrelated, issues were selected and used to produce a new diagram, varying these two from low to high to set up the axes. The four different future scenarios, represented by the quadrants in the new diagram, illustrated four very different future worlds. A robust strategy for the new product should be successful in all these different scenarios. These four different scenarios were explored by the team in order to provide an understanding of these requirements.

J. Continuous considerations of potential sustainability impacts of new materials

A material checklist template was developed to help material developers continuously consider potential sustainability challenges and the opportunities of new materials at a very early stage. The check-list was intended to be used for every new material that was produced in laboratory scale within the project.

K. Regular illustrations of the sustainability performance and potential trade-offs

'Sustainability profiles', graphic representations of the considered aspects and the relative performance of the new product in comparison to the reference for each aspect, were used to visualize the current overall performance of the new product. These profiles were updated regularly as more knowledge about the product system, relevant assessment parameters, and the resulting sustainability performance emerged. The profiles illustrated the progress in the project and which aspects that at each time constituted the greatest challenges, and they also highlighted the need for handling trade-offs in a structured and transparent way.

Reflections on experiences

While performing the above-mentioned activities in an effort to iteratively develop an understanding of the sustainability performance of the emerging product system in the project (Figure 1), action research was carried out in order to develop methodologies to be used later in the ongoing project and, in a generalized way, also in other projects. Experiences of the sustainability assessment activities, in particular barriers that hampered progress, will be reflected on here and are summed up in four main lessons learned.

Knowledge sharing activities may encounter organizational defensive routines. In projects in which several different organizations are involved, intellectual property issues and cultural clashes can be expected. In the project, participants indicated concern about sharing information. It can be speculated that when employees do not know what should be treated as a secret for intellectual property or other reasons, everything is treated as a secret to be on the safe side. Argyris and Schön talk about organizational defensive routines as any policy or practice that protects organizations from embarrassment or threat and at the same time prevents them from identifying and reducing the cause of embarrassment or threat (Argyris & Schön 1989). According to Argyris, organizational defensive routines are anti-learning and overprotective (Argyris 1986). It is important that the assessor is aware that such routines most probably will surface, especially in projects in which several different organizations are involved, and is prepared for both proactive and reactive responses.

Assessment activities may be seen as threats if results are expected to be unfavorable. In the project, some resistance to assessment activities at an early stage in the project was experienced. The assessor noted concern among team members about quantitative calculations based on preliminary data, perhaps because of the fear that scientifically interesting routes would not be pursued if they indicated major challenges to sustainability. There were also occasions when individuals expressed a desire to know the results before the work had been carried out, presumably to ensure that the results would not challenge other on-going activities. This can potentially be seen as another example of organizational defensive routines as described above.

It is important to understand how participants perceive the goals of the project and what their assumptions are regarding their own and the assessor's role. Many times throughout the chain of activities, it became apparent that the perceptions about the idea of the process and the roles of different participants varied greatly among team members. The assessor experienced that several of the notions described in this article as underlying the process, e.g., the need for future-orientation and the important role of team learning, were not fully understood and accepted by the whole team, which created unnecessary tension in some activities. Furthermore, the assessor sometimes sensed reluctance among team members to become involved in value-based decisions in the sustainability assessment procedure, perhaps because they believe that this is something that should be left to the management of the company, or that a sustainability assessment can be based on objective truths and expert statements. It is believed that some participants did not have the same notion as the assessor, at the start of the project, that to be guided by a sustainability assessment requires interaction to a larger extent than being handed sustainability design requirements. One reason behind this might be the belief that changing from petroleum-based to bio-based material almost automatically makes the product more sustainable and that the role of the sustainability assessment project is to prove this rather than to help developers maneuver through a challenging task. Another reason might be that the participants did not see it as their role to discuss what sustainability entails since this may be seen as interfering with management tasks. The sustainability assessor, on the other hand, had the intention to go further and make the developers aware of important sustainability aspects so that they could make decisions in the direction of a more sustainable product. In hindsight, an initial inventory of the participants' perceived role in the process would have been beneficial in order to plan for modifying either the process or participants' perceptions of their role and of the process. The role of the sustainability assessment subproject should, at the very least, have been discussed in more detail at the start of the project. Thus, in projects of this type, it would be useful to identify challenges to integrating learning and achieving change by learning more about the participants' different needs, their attitudes towards the project and their power to act, at an early phase in the project. One way to do this is by performing a stakeholder analysis (Bell & Morse 2008).

It is important to motivate the team to take part in discussions and learn more about important sustainability aspects. Because of the major importance of decisions made by the material development team in developing a more sustainable product, efforts to describe the large impact that their decisions have on the sustainability of the final product to motivate them to participate in team-learning activities may be needed. One experience from the project was that project members were not always convinced of the importance of learning about how they could influence development. It is believed that efforts aimed at preparing and motivating participants to direct more attention to joint sustainability assessment activities would have been fruitful. In a different but related field, motivation was identified as a key factor in terms of whether or not university teachers strive for the integration of sustainability issues into the curriculum (Svanström et al. 2012). Both the attitudes and competences of the teachers as well as whether they were pushed or hindered by the university system, were seen as target areas for efforts to improve the integration of sustainability. Most likely, similar issues are important in terms of material developers' likelihood of integrating sustainability issues into their work. Their important role in the task, as they make everyday decisions during the process that will strongly influence the sustainability of the product, must be demonstrated to them, and they need to be convinced that their efforts are requested by their organization and will be rewarded and appreciated.

The lessons learned from reflecting on activities within the project were used, together with ideas and findings from literature, in putting together a suggested process for guiding material development when the goal is to achieve more sustainable products. The suggested process can function as support to the assessor in setting up more detailed activities in different types of projects with more sustainable products as an overall goal. Inspiration to specific activities may be found in the descriptions provided earlier in this paper, but activities must be tailor-made to suit the needs and opportunities of each specific project.

Suggested process for guiding material development towards more sustainable products

The material developers strongly affect the sustainability performance of a finished product. To make it possible for them to make choices towards a more sustainable final product, and if needed, even rethink the product idea based on more holistic considerations, developers need to be aware of *and* fully grasp which surrounding world and future-oriented considerations that may make significant impacts on the specific product's sustainability performance. It is not enough to provide developers with a list of parameters, e.g., acidification potential and global warming potential, with values that need to be lowered, they also need support in translating and integrating the parameters into something that can guide each team member in their individual area of expertise *and* in developing a more holistic understanding of the product system. This is the background to the suggested continuous learning process described below. The need to address different actors' specific needs in performing and communicating sustainability assessments was highlighted by Löfgren (Löfgren 2012) in a doctoral thesis.

To be able to motivate participation in the process, it is important that the assessor understands the role of each project member and their expectations on the project. This understanding is necessary for the assessor to be able to communicate with other participants and to set up an appropriate process. A stakeholder analysis or similar analysis giving insight into which roles the participants expect to take in the project and what they expect from the assessor is therefore highly recommended to do before the work starts, and will most probably result in a more successful project. Furthermore, the risk of encountering different organizational defensive routines should always be kept in mind when planning and carrying out the project. It may also be helpful if the process is briefly outlined for the team before it is started and that each team member commits to participating in the process. Also, to enable functional communication in the suggested process, it would be useful to limit the core team to a maximum of ten to twelve participants.

Defining the long-term goal and determining scope

The first step of the suggested process is to make the whole project team aware of the considerations that may have a significant impact on the specific product's sustainability as seen from a holistic and future-oriented perspective. This is illustrated in Figure 2 as defining the long-term goal and determining scope.

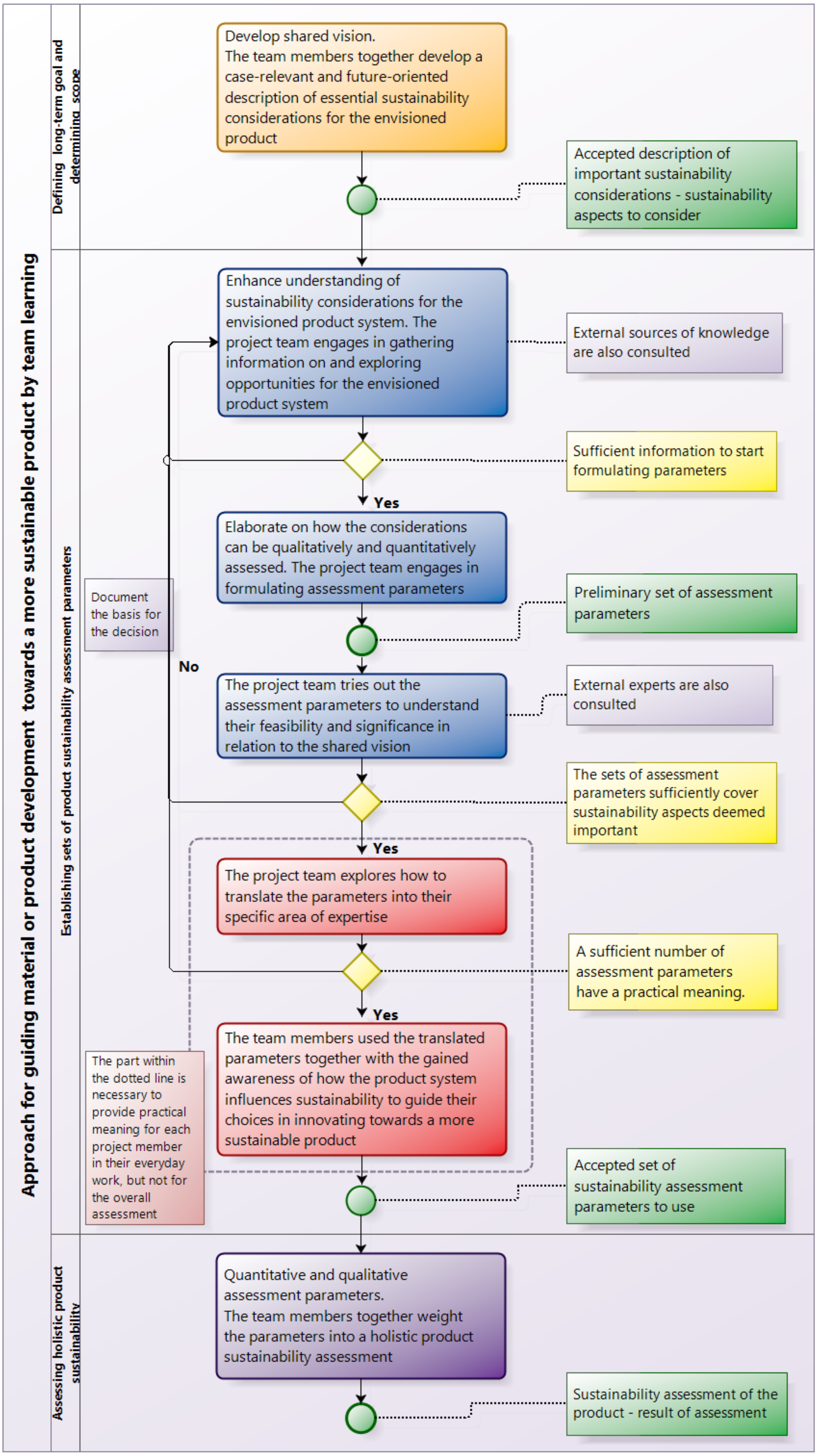
Approach for guiding material or product development towards a more sustainable product by team learning
Defining long-term goal and determining scope
Develop shared vision.
The team members together develop a case-relevant and future-oriented description of essential sustainability considerations for the envisioned product
Accepted description of important sustainability considerations - sustainability aspects to consider
Establishing sets of product sustainability assessment parameters
Enhance understanding of sustainability considerations for the envisioned product system. The project team engages in gathering information on and exploring opportunities for the envisioned product system
External sources of knowledge are also consulted
Sufficient information to start formulating parameters
Yes
Elaborate on how the considerations can be qualitatively and quantitatively assessed. The project team engages in formulating assessment parameters
Preliminary set of assessment parameters
Document the basis for the decision
No
The project team tries out the assessment parameters to understand their feasibility and significance in relation to the shared vision
External experts are also consulted
The sets of assessment parameters sufficiently cover sustainability aspects deemed important
Yes
The project team explores how to translate the parameters into their specific area of expertise
A sufficient number of assessment parameters have a practical meaning.
Yes
The team members used the translated parameters together with the gained awareness of how the product system influences sustainability to guide their choices in innovating towards a more sustainable product
The part within the dotted line is necessary to provide practical meaning for each project member in their everyday work, but not for the overall assessment
Accepted set of sustainability assessment parameters to use
Assessing holistic product sustainability
Quantitative and qualitative assessment parameters.
The team members together weight the parameters into a holistic product sustainability assessment
Sustainability assessment of the product - result of assessment

Figure 2. *The suggested process for guiding material and product development projects towards more sustainable products. Through team involvement during material or product development, a shared goal and relevant sets of product sustainability assessment parameters for a specific product are established. Note that the whole process is lead by a sustainability assessor in an iterative process, but such features are excluded from the scheme for clarity reasons.*

A shared vision is needed both to define the target and the scope for the material or product development process and for efficient intra-project communication (Hong et al. 2011, Lackus & Kolar 2007). If the goal of a project is to obtain 'a more sustainable final product,' then visualizing and describing what the qualities of this 'more sustainable final product' can be are vital. This should be done by the whole project team, together with other important stakeholders, in order to make sure that knowledge from many different areas and multiple points of view are included in the process. The project team members can then increase their awareness of important considerations and develop an understanding and acceptance of the project's description of a 'sustainable final product'. When the description of the goal is developed together, a common language will evolve that will enable more effective intra-project communication.

In developing the description of a more sustainable product for the project, an appropriate time-frame must be applied and uncertainties about future developments in society must be handled in a satisfactory way. Approaches are available that handle such uncertainties as well as how the product affects and is affected by the surrounding world, such as the activities 'C' and 'I' described above. 'Brainfiring' can be a useful procedure (Härén 2004); brainfiring suggests working in groups to rephrase a problem in a variety of different ways, in contrast to brainstorming which focuses on coming up with as many ideas as possible in the formulation of one problem.

In Figure 2, 'sustainability aspects' refer to areas such as biodiversity, climate, safety and health, operational cost, availability of raw material, and other areas of sustainability that may be influenced by choices made in product development. The project's case-specific description of 'sustainable final product' should include the areas that need to be assessed - the relevant product sustainability aspects - and how to handle trade-offs between these areas as well as uncertainties and data gaps. This description will form the goal and scope for the development project, and for the assessment work. The description should be revised when needed, i.e., with changes in circumstances or new knowledge. The suggested process, therefore, is set up to allow for going back and adjusting the direction of development, i.e., iterating.

Establishing sets of product sustainability parameters

Each sustainability aspect identified in the first step can be described by one or several 'assessment parameters'. The second step in guiding towards a more sustainable final product is to establish sets of relevant assessment parameters in a team-learning process, including translating the assessment parameters into parameters that are relevant for the participants' specific tasks. This last step of translating the parameters is an act of inviting the team to find out how they in their work affect product sustainability instead of telling them what to improve or to avoid in terms not clearly connected to their work, which is what is conventionally done. If the parameters are not integrated into something that is meaningful in relation to each participant's expertise and everyday work, the participants cannot utilize their skills towards the goal of a more sustainable final product since they lack direction.

In the suggested process (Figure 2), the part of establishing sets of product sustainability parameters is divided into several sub-steps. First, information about the identified sustainability aspects is gathered by the assessor for the product's entire life cycle (the product system) from literature, stakeholders and experts. The assessor is advised and assisted by the project team. The information is then refined by the assessor, for example, by using estimates and statistics as in the activities 'D' and 'E' described above.

To avoid overlooking relevant parameters, the preliminary sets (plural because there may be different sets for different scenarios or team members) of assessment parameters should be reviewed both by employees with other expertise within the company and by external experts. Examples of external experts are scientists in the field, or representatives from trade organizations or non-governmental organizations. The sets should also be evaluated in relation to the coverage of the sustainability aspects deemed important in the project and also in terms of significance and the feasibility of assessing the parameters. Two activities described above, 'F' and 'G', are examples of how a team can evaluate and explore parameters.

If a set of assessment parameters is found not to sufficiently cover the sustainability aspects deemed important, then iteration is needed. If sufficient, the identified product sustainability assessment parameters should be explored; ways of translating and integrating them into each team member's specific area of expertise and everyday work should be discussed. In practice, this can be done as described above for activity 'H'. It is vital for guiding product development towards a more sustainable product that the project team not only understands and accepts the assessment parameters but that they can relate to them in their daily work. When the project team develops knowledge of how their daily work impacts the sustainability of the final product, the opportunity to make decisions towards an improved result becomes greater. If it is difficult to improve the performance of the envisioned product for the selectedparameters, then the knowledge of holistic and future-oriented considerations acquired when defining the long-term goal and determining scope can be a base for rethinking and coming up with new ways of improving the sustainability of the final product.

Assessing holistic product sustainability

When sets of sustainability assessment parameters have been agreed on, an assessment of the impact of the product system(s) can be performed. Reaching agreement and acceptance within the project team of the relative weights of different parameters should be less complicated when everyone has been involved in the process of establishing the sets of sustainability parameters. In other words, different views, or value-systems, should have appeared, been discussed and taken into account earlier on in the process. Different value-systems can also be applied in weighting in order to illustrate the potential effect on the final result, to enable a more holistic understanding of the implications of the results. Product sustainability assessment should be performed several times during a material or product development process to provide input to an, by necessity, iterative process, as described in Figure 1. The activity 'K' described above gives an example. The assessment is improved with the new knowledge gained of the product system and of relevant sustainability parameters each time it is performed. This type of holistic approach is only sparsely discussed in literature and more research is needed (Clancy et al. 2013), whereas data inventory and weighting procedures are thoroughly discussed in the literature (European Commission 2009, Finnveden 1999, Finnveden et al. 2009, Pennington et al. 2004, Rebitzer et al. 2004). To obtain a greater understanding of possible interpretations of the result, the whole team should be involved in establishing and exploring the weighting in the suggested process.

To sum up, the suggested process (Figure 2) for guiding material and product development projects towards more sustainable products emphasizes the joint learning process of the team – with a specific focus on facilitating innovation towards more sustainable products by translating and integrating significant product sustainability characteristics into each team member's specific area of expertise and everyday work. The simultaneous use of external expertise, like stakeholders, NGOs and scientists, is crucial in order not to miss important views and knowledge. One goal is that this process leads to continuous knowledge enhancement throughout the product development process and to the reporting and discussion of results within the team. This is an iterative process which should continue until the product is available for sale, allowing the product sustainability parameters to be modified during the process to include new knowledge. Consequently, the assessments will improve with time. The learning potentially achieved in a process like this will also be useful in later projects and may therefore create valuable spin-off effects.

Conclusions

The development of more sustainable products requires relevant and future-oriented assessment parameters early in the stages of material or product development - where choices that determine many of the sustainability burdens of a product are made. Material or product development for more sustainable products might require rethinking and for the purpose of managing this, the whole project team needs to become aware of potential future world development, and understand how considerations in their everyday development work can affect the final product's sustainability performance. Approaches for handling this complexity in material or product development stages have not been found in literature and therefore, a team-learning approach that deals with these issues is suggested.

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Paper III

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 [3], 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 [4-5]. 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 [6-8]. Building on structures that nature creates demands less modification but often more separation of unwanted materials and specificity in reactions.

A biomass-based material is not inherently better in all aspects compared to a fossil-based material [3]. Therefore, a pure focus on shifting to renewable resources might not be enough. The entire life cycle needs to be assessed in order to reveal this [9]. 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 [10]. 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 [11]. 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 [12]. The second common way to use LCA in product development is to assess proposed changes. An example could be to consider a change in a process, a part or a material and evaluate the estimated LCA result of that change by a so called "quick and dirty" comparative LCA [13]. 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, i.e. 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 study do not often involve the knowledge and experience of the product development team 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 is to 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 more 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 [14]. 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. However, there are potential effects on many different areas that should be assessed before this can be evaluated. 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 based 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 different stages, e.g. 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 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. In both the low and the high wood cases, the production

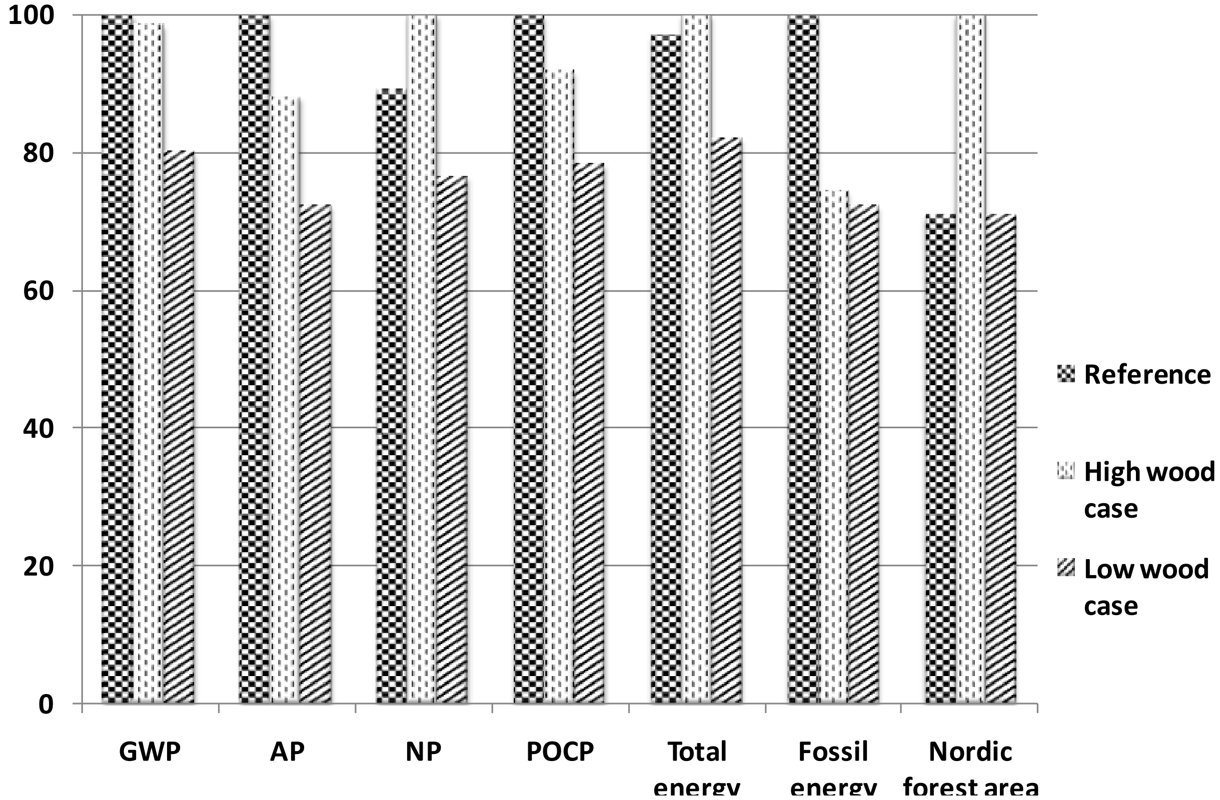

Fig. 1: Cradle-to-grave LCA estimation of diapers – the reference diaper is compared to high and low wood cases, presented as percentage relative to the highest contributor [1-2].

the reference. 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 process transforming fluff pulp into a new material has been 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 considering all relevant sustainability aspects performs better than the replaced material. 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 '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 translated into LCA impacts. Fig. 2 illustrates the cradle-to-gate LCA of the reference 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.

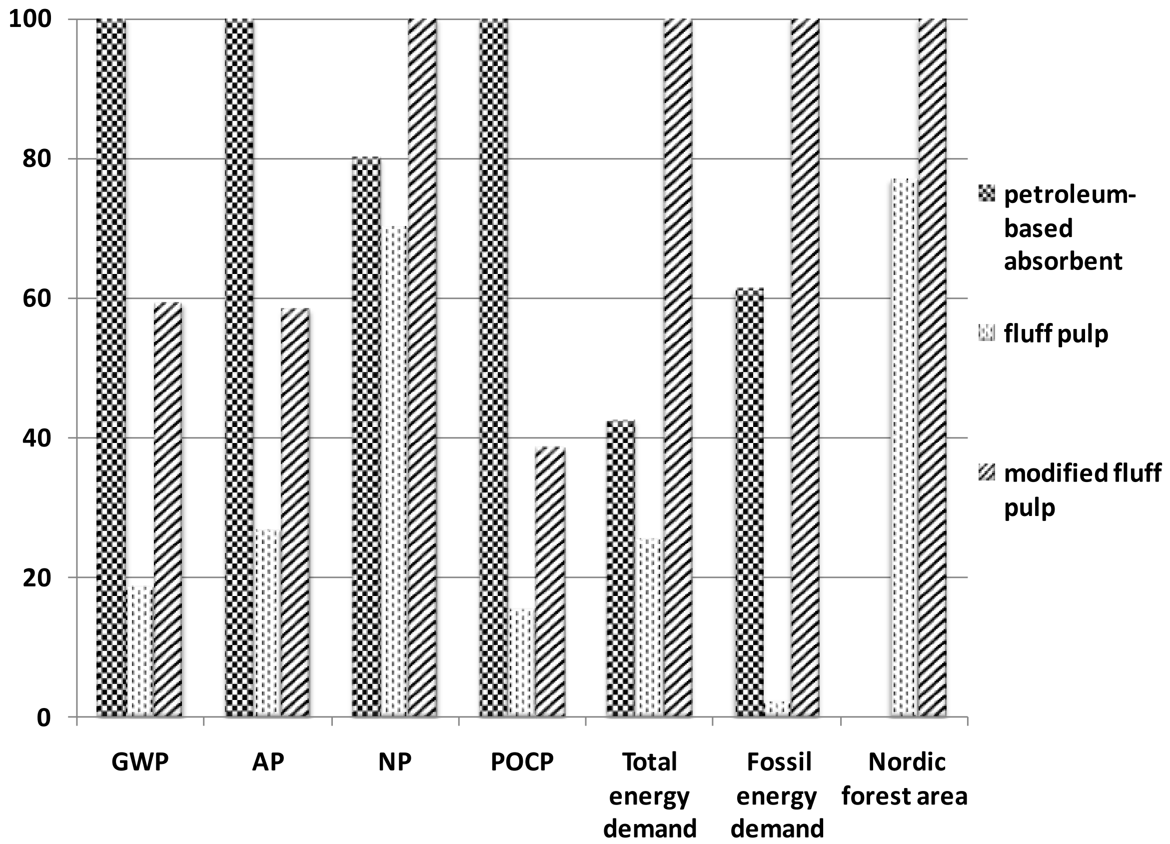

Fig. 2: Cradle-to-gate LCA results per kilo for petroleum-based absorbent material, fluff pulp and modified fluff pulp presented as percentage relative to the highest contributor [1-2].

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. Fig. 2 illustrates the challenges in several impact categories for this stage when changing to a renewable resource. Changes that result in improvements in the diaper material stage may, however, have detrimental effects in other stages, e.g. if use or waste management is affected negatively. Therefore, the whole life cycle of the product needs to be evaluated as early on as possible to guide the material development process.

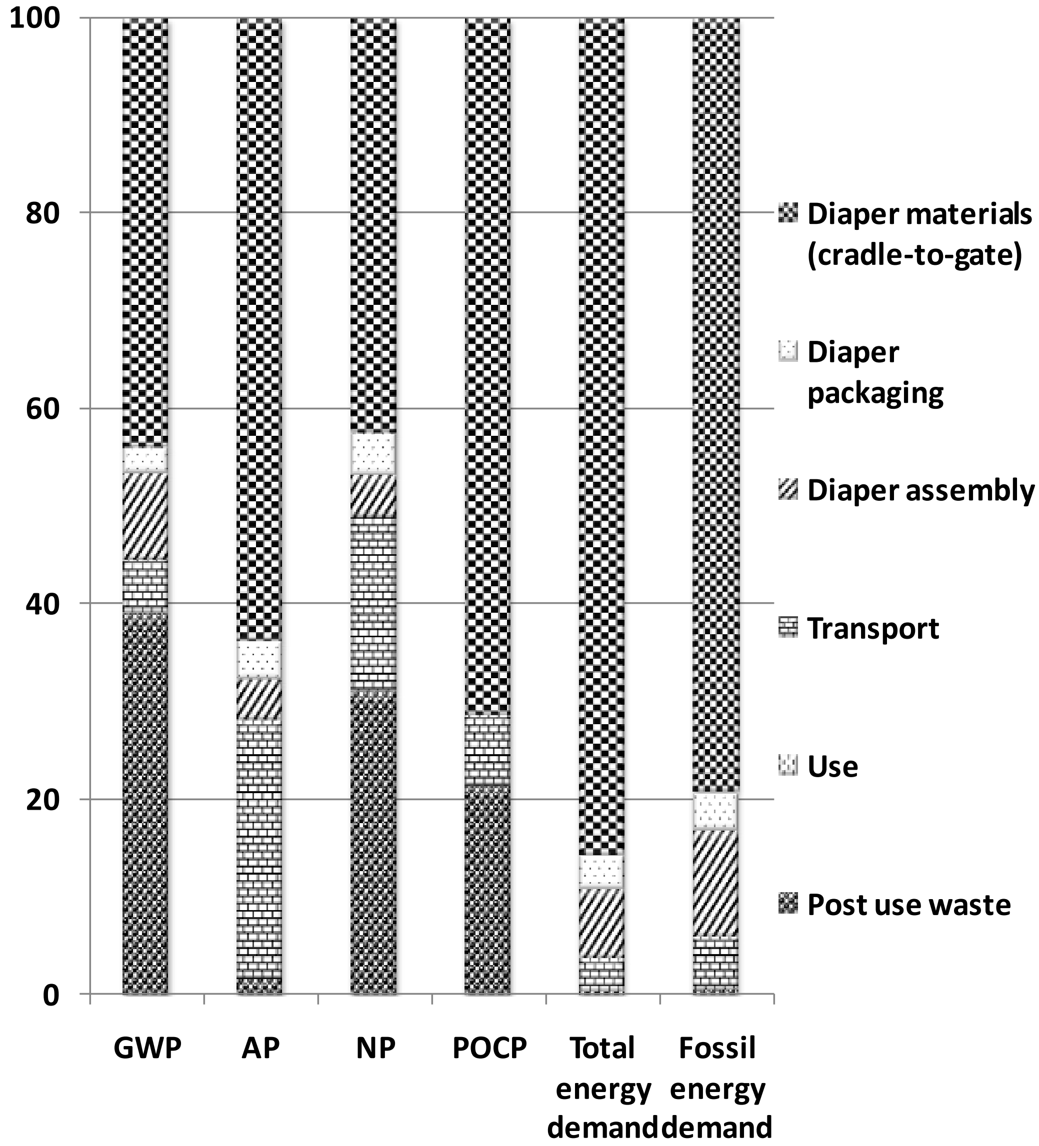

Fig. 3: Environmental impact of the reference diaper divided into four life cycle stages, presented as a percentage of total impacts, for four commonly used impact categories [1-2].

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 intended 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 that the material development team is more used to 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.

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 considerations of relevant sustainability aspects along the entire life cycle of the product 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 LCA studies, 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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