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Abstract

The utilization of wood in long life products, such as construction materials in the built environment, is an effective way to optimize the use of natural resources while also reducing negative environmental impacts. However, the environmental benefits of timber, especially in the construction sector, are not always clearly understood. As a renewable material, timber is available in perpetuity if it is obtained from sustainably managed forests. Using timber in the built environment stores sequestered atmospheric carbon dioxide in long-life products and timber can be incinerated at the end of its life (or its multiple lives) with energy recovery, thereby minimizing demolition waste. The built environment effectively acts as an extension of the forest. The question is: how should the environmental benefits of timber use be measured and presented? To answer that question, this paper offers an overview of the life cycle assessment (LCA) methods the forest products sector could broadly apply to evaluate and report the sustainability performance of wood. In addition to environmental LCA, the paper also incorporates an overview of organizational LCA (O-LCA), and social LCA (S-LCA). Furthermore, this paper discusses environmental product declarations (EPDs) and construction standards aiming to enable better comparability of the environmental performance of products. This review paper concludes with a discussion of where the opportunities for the forest products sector lie and the need for joint actions within the sector. The importance of including the storage of sequestered atmospheric carbon dioxide into the standards assessing the environmental impact is emphasized.

Keywords: environmental impact, environmental product declaration (EPD), forest products, life cycle assessment (LCA), O-LCA, product category rules (PCR), S-LCA, wood

1 Introduction

Wood is a natural, renewable, reusable, and recyclable raw material that can play an important role in minimizing negative effects on the climate and environment

when it is sourced from sustainably-managed forests (Hill 2011). Forest biomass is currently the most important source of renewable energy and now accounts for approximately half of the EU's total renewable energy consumption (EC 2013). Wood products can contribute to climate change mitigation as they act as a carbon pool during their service lives by withdrawing CO₂ from its natural cycle. Furthermore, wood products can substitute for more energy-intensive products (such as cement, steel, or aluminum) in the built environment and their inherent energy content can be recovered at the end of their service lives, substituting for fossil fuels when they are incinerated. However, it is important that the correct sustainability assessment tools are applied to better understand the benefits of using wood products.

While wood-based products promise to offer economic, environmental and societal benefits, these

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benefits need to be properly quantified. This requires using tools that can properly assess and compare sustainability benefits of different. Wood-based products, from raw materials to intermediate and final products, need to be subjected to detailed Life Cycle Assessment (LCA), considering use and disposal or re-use to fully evaluate their claimed benefits. This is necessary to provide solid evidence for supporting policy decisions, such as policies to encourage building with wood, as well as to support claims of superior environmental credentials, particularly when compared with non-renewable materials. Product quality standards, certification programs, environmental labelling, industry-led schemes, and communication tools are important to encourage demand and provide environmental information to consumers and other stakeholders. Industries associated with non-renewable materials are putting considerable effort into conducting LCAs and publishing environmental product declarations (EPDs) of their products; it is important that the forest products sector does not get left behind. LCA is a tool that has been developed to analyze and quantify the environmental burdens associated with the production, use, and disposal of a product and is arguably the best way of quantifying this information (Hill 2011). For the purposes of this review, the term *product* includes both goods and services.

Due to consumer pressure and government legislation at national and regional levels, the environmental impacts of products are increasingly coming into focus. Many companies now make environmental claims about their products to boost sales and it is desirable to back up such claims with verifiable data which can be achieved by conducting LCAs. This introduces a potential tension because companies tend to keep details of manufacturing secret, and LCA process requires transparency. Another use of conducting an LCA is to reduce the environmental footprint associated with the manufacturing of a product. In this case, LCA can be used as an analytical tool to identify where major environmental impacts arise and determine appropriate actions to reduce these impacts. A valuable outcome from an LCA study is the identification of 'hot-spots,' which are parts of a process associated with the most significant environmental burdens, where investment in process improvements will result in the greatest environmental benefits.

Interest in LCA grew rapidly during the 1990's and generated high expectations, but also became the focus

of criticism (Ayres 1995, De Haes 1993, Ehrenfeld 1997, Finnveden 2000, Krozer and Vis 1998). However, since the beginning of the 21st century, considerable progress has been made, including the development of international standards. There are also several international initiatives taking place with the aim of building consensus and developing robust methodologies. These include the Life Cycle Initiative of the United Nations Environment Program (UNEP), the Society of Environmental Toxicology and Chemistry (SETAC), the European Platform for LCA of the European Commission (EPLCA) and the International Reference Life Cycle Data System (ILCD). Life cycle assessment is not static and there are ongoing programs dealing with improving various aspects of this methodology (Finnveden et al. 2009). It is important that the correct decisions are made regarding the choice of materials for the built environment and LCA can be used as a means of informing those choices. However, it entails that LCA is properly used and that decision support tools allow for accurate comparability between products (Audenaert et al. 2012, Ding 2008, Forsberg and Von Malmborg 2004).

The common LCA methodology is defined in ISO 14040 (ISO 2006a) and ISO 14044 (ISO 2006b). Since the 1980s, when LCA analysis was first developed, numerous methodologies to classify, characterize, and normalize environmental effects have been developed. The most common are focused on the following environmental impact indicators: acidification, eutrophication, thinning of the ozone layer, various types of ecotoxicity, air contaminants, resource usage and green-house gas emissions.

The LCA methodology was originally developed for products. Recently, however, its application at the organizational level is becoming more and more relevant, leading to the introduction of the so-called Organizational LCA (O-LCA). This includes more than one product life cycle, as most organizations are engaged in many product life cycles to different degrees and a large part of organizations' environmental impacts can reside outside the organization's boundaries- upstream and downstream in the value chain. Guidance on O-LCA is included in the Technical Specification ISO/TS 14072 (ISO 2014). ISO/TS 14072 extends the application of ISO 14040 and ISO 14044 to all activities of the organization. O-LCA also follows the four-steps defined in ISO 14044. The main differences between LCA and O-LCA reside at the scope level and boundary definition (Martínez-

Blanco et al. 2015a,b). In O-LCA, the unit of analysis is the organization and its portfolio, which is unique for each organization.

Recent methodological developments have aimed at extending life cycle thinking to also evaluate social issues, referred to as Social life cycle assessment (S-LCA), and economic issues, referred to as Life Cycle Costing (LCC), towards a complete and comprehensive Life Cycle Sustainability Assessment (LCSA). Similar to LCA, S-LCA integrates traditional life cycle assessment methodological steps while having social impacts as its focus (Sala et al. 2015). The basic phases of LCA defined by ISO 14044 are also applied in S-LCA, including (i) scope and goal of the assessment; (ii) inventory of impacts; (iii) impact assessment with proper indicators (e.g., child labor, forced labor, health and safety, etc.); and (iv) interpretation of the results. These methodologies differ from the mere reporting of data, such as emissions from a factory, in that they consider the consequences of these activities on society.

In this paper, LCA of products as well as organizations are presented, aiming to deliver a comprehensive overview of environmental impact assessments to include assessments of environmental impact, social impact, and economic impact. The paper moves on to discuss the importance of these assessments in the context of the forest/wood products sector.

2 LCA Methodology

To conduct an LCA, it is necessary to determine the appropriate goal and scope (i.e. what is the purpose behind conducting a LCA and what is being included in the study). The scope must define the system boundaries in the study and declare the functional unit. For many purposes, the system boundary can be defined as 'cradle to gate,' that is, from the manufacture of a specific product in a factory to the point at which it leaves the facility (corresponding to modules A1-A3 in the European Standard EN 15804 (CEN 2012)). This provides the most accurate LCA because this phase of a product life cycle involves the fewest assumptions and the data gathering process is relatively straightforward. However, a low impact product, as determined through a cradle to gate analysis, may require a lot of maintenance during the in-service phase of the life cycle, or there may be serious environmental impacts associated with disposal. A full appreciation and understanding of the

environmental impacts associated with a product choice therefore requires the entire life cycle to be considered. This invariably introduces a higher level of uncertainty into the process because there may be aspects of the life cycle that are not well understood, thus requiring assumptions to be made. These assumptions may have a very significant impact upon an LCA and a bias may be introduced if comparisons are being made between different products.

Defining the goal and scope involves writing a series of statements at the beginning of the process to tell the reader why the LCA was performed, who is conducting the study, who the client is, and what is covered by the LCA. It is at this stage that the system boundary is defined. For example, the purpose may be to conduct an LCA of only the manufacturing process (i.e., cradle to factory gate) or of the entire service life. Additional parts of the lifecycle, such as recycling and disposal, may also be analyzed. The purpose of the LCA may simply be to report the environmental burdens associated with a product or process, referred to as an attributional LCA, or to examine the consequences of changing various parameters or adopting different scenarios, referred to as a consequential LCA (Frischknecht and Stucki 2010, Gala and Raugai 2015). It is also necessary to specify the subject of the LCA. This is referred to as the declared unit if cradle to factory gate is being analyzed, or the functional unit if other parts of the lifecycle are also being studied. Another important consideration when studying the environmental impacts associated with a product or process is the timescale involved and it is important that this is also defined at the preliminary stage. It is also a requirement to specify which allocation procedures will be used during the analysis.

The life cycle inventory (LCI) phase of the analysis requires a compilation of all information about the selected process. To do this, an imaginary system boundary is drawn around the process and all the material and energy inputs and outputs are quantified. This process is usually divided into the different life cycle stages, including manufacture, service life, end of life, and disposal. Data gaps are identified once the LCI phase of the analysis is complete. In some cases, it is possible to collect the missing data; where doing so is not possible, 'reasonable' assumptions must be made. During this phase, mass balance calculations are also performed. This is a very useful tool for identifying data gaps and is based on the principle that the mass of all matter go-

ing into the system under study should equal that of all the matter exiting the system. At some stage, the data gathering process must be terminated and the point at which this occurs is determined by cut-off criteria. Data falls into two principal categories: primary (foreground) and secondary (background) data. Primary data is that which has been gathered by the LCA practitioner and may include utility bills, delivery notes, and other information that is directly linked to the process. Secondary data is that which has not been directly obtained, but is more generic in nature; for example, if wooden pallets are used to ship the product, then it is highly unlikely that a full inventory of the pallets would be made. This information may be sourced from a database, such as Ecoinvent. The collection and analysis of data invariably leads to issues regarding commercial confidentiality, which can cause problems, especially when the LCA must meet adequate levels of transparency to be credible. Ultimately, what should result from such an analysis is a table, referred to as an input-output table that represents flows of materials and energy to and from the natural environment (i.e., the ecosphere).

Once the LCI phase has been completed, it is necessary to quantify environmental burdens. This is called the life cycle impact assessment (LCIA) phase. During this phase, there are several additional complications that should be considered. The biggest problem involves deciding how to report environmental impacts. There is ongoing discussion regarding how to properly report environmental burdens, but a consensus has been developing over the past decade or so. The objective involves aggregating environmental implications associated with flows to and from the natural environment into a small, but nonetheless meaningful, set of indicators. This methodology has essentially broken down into two main approaches, including midpoint and endpoint indicators (Bare et al. 2000, Ortiz et al. 2009, Hauschild et al. 2013). In the midpoint approach, environmental burdens are grouped into similar environmental impact categories (e.g., global warming potential, ozone layer depletion, freshwater eutrophication, etc.). In comparison, the endpoint approach seeks to model the chain of cause and effect to the point of the evaluation of damage (e.g. incidence of skin cancer rather than ozone layer depletion is reported). This makes for simpler reporting with fewer indicators, but involves a higher level of uncertainty. The midpoint approach is preferred because of the higher level of accuracy, but can be more dif-

ficult to interpret (Dong et al. 2014). Impact categories are reported in terms of effect on human health (e.g., disability adjusted life years (DALY)), or on ecosystems (e.g., species loss). Some systems have even gone so far as to aggregate all impacts into one category (e.g., ecopoints), but values reported using this approach have such high uncertainties that they're effectively meaningless. Environmental impacts are calculated using a variety of models, currently more than 150, which attempt to determine the impacts of processes on the natural environment. Examples of such models include:

- Midpoint: Tool for the Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI), University of Leiden Institute of Environmental Sciences method – Centrum Milieukund Leiden (CML), Environmental Development of Industrial Products (EDIP)
- Endpoint: Eco-indicator, Life Cycle Assessment Method based on Endpoint Modelling (LIME)
- Combined midpoint and endpoint: ReCiPe (the acronym represents the initials of the main developers of the method), IMPACT 2002+

For example, applying IMPACT 2002+, the 'value' of an environmental impact is reported as an ecoindicator and measured in environmental points. The accumulated ecoindicator is composed of damage categories (e.g., human health, ecosystem quality, climate change, resources) and impact categories (e.g., carcinogens, non-carcinogens, respiratory inorganics, respiratory organics, ionizing radiation, ozone layer depletion, aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acidification, land occupation, aquatic acidification, aquatic eutrophication, global warming potential, non-renewable energy, mineral extraction). This requires a weighting process to be applied, which is reliant on value judgement.

The impact categories selected should provide useful information about the product or process while taking the goal and scope of the study into consideration. When selecting the impact categories, it is also necessary to select characterization factors, which are the units used to report each environmental burden. To consider the example of the climate change impact category, the characterization factor for this category involves global warming potential over a 100-year timeframe (GWP_{100}) measured in kilogram CO_2 equivalents. The method used to calculate impacts affect the results of the LCA

study, which should always be considered when making comparisons between products or materials in different studies (Monteiro and Freire 2012).

Another important factor involves the correct allocation of environmental burdens on different co-products when the system under analysis produces more than one product. Examples of this include the allocations between cereal and straw, or meat and wool in agricultural production systems (Brankatschk and Finkbeiner 2014). Ideally, allocation should be avoided when possible but, in many cases, this cannot be done and a choice must be made regarding the allocation procedure used. Various approaches can be used for allocating environmental burdens, including mass, energy, or economic allocation. Guidance regarding allocation is given in ISO 14040 and ISO 14044, both of which recommend a hierarchy of choice for allocation methods. In many cases, economic allocation is used, which provides a more realistic allocation of burdens because economic concerns often justify processes used. Problems with this method include price fluctuations and unavailability of important economic information. An advantage of mass allocation is that it does not vary, however, a disproportionate burden may be assigned to a waste or co-product. One method of dealing with allocation issues is to employ a system expansion so that all the different product streams are included within the same system boundary. For comparison purposes, the wood-based functional unit must be the same as the non-wood-based functional unit. For example, if a timber frame building is manufactured using waste from the process used to produce energy, then it is possible to make the functional unit 'the structural frame plus the production of x kWh of energy'. This could be compared with the same structural functional unit made from a non-renewable material plus x kWh of energy produced from a fossil fuel. However, if the wood waste goes to the production of chipboard or paper, then the comparison becomes more difficult. It is almost inevitable that some form of allocation will have to be employed. In many cases, an economic allocation may be the best way of allocating burdens but, again, prices may fluctuate. Furthermore, forests can produce different product streams at different times (e.g., first thinnings, second thinnings, third thinnings, harvest), which adds to the problem of economic allocation over a time scale that can be as long as a century (Jungmeier et al. 2002).

Jungmeier et al. (2002) identified ten different processes in the forestry value chain where allocation issues can occur: forestry, sawmill, wood industry, pulp and paper industry, particle board industry, recycling of paper, recycling of wood-based boards, recycling of waste wood, combined heat and power production, and landfill processes. These can be divided into multi-output processes (e.g., sawmill) or multi-input processes (e.g., landfill or domestic waste incineration plant).

At the end of the LCA process, there are additional analyses that can be performed; these include normalization, grouping (aggregation), and weighting. These are usually used to make environmental information more comprehensible (Chau et al. 2015).

3 Life Cycle Assessment and Environmental Product Declarations

LCA is a useful tool when it is used correctly. However, problems can arise when LCA is used to make comparative assertions between different products. There is considerable scope for variation in the way that LCA is performed (e.g., choice of system boundary, functional unit, environmental impact categories and calculation methods, assumptions about service life, maintenance, etc.), which can make comparisons between products problematic, if not impossible. A limitation of LCA involves the insufficient transparency of results, which can hinder the utilization of existing studies as a source of information and in making comparisons. To compare LCAs with confidence, the datasheet, assumptions, sources of data, and calculations should be provided. Due to the use of commercial software, transparency is often lacking. For the wood sector and other bio-based products, it is particularly important to present system boundaries, functional units, and co-product allocation transparently. It is important to include agricultural activities as well as any change in land use for agricultural inputs. For example, old-growth forests represent a significant carbon pool; disturbing such forests could lead to the release of substantial carbon. Furthermore, a direct LCA comparison can only be done on the same functional unit, which considers the actual function of the product. If a comparison is performed on a mass basis, the comparison is meaningless when the alternative product has a different lifetime or is used or disposed of in a different way.

Clearly, there is considerable potential for uncertainties to influence LCA. Nevertheless, considerable progress has been made in this arena in the past decade. One of the most significant developments has been the introduction of EPDs. In order to develop a framework that allows for the comparability of environmental performance of different products, ISO 14025 (ISO 2006c) was introduced. ISO 14025 describes the procedures required to produce Type III environmental declarations (or environmental product declarations). This framework is based on the principle of developing product category rules (PCRs), which specify how information from an LCA is to be used to produce an EPD. A PCR will, for example, specify what the declared unit and/or functional unit is for the product.

Within the framework of ISO 14025, only the production phase (i.e., cradle to gate) of the lifecycle should be included in the EPD. It is also possible to include other lifecycle stages, such as the in-service stage and the end of life stage, but these are not required. ISO 14025 also gives guidance on the process of managing an EPD program. This requires program operators to set up a scheme for the publication of a PCR under the guidance of general program instructions. There has been a range of EPD programs initiated since the publication of ISO 14025 (Del Borghi 2013), resulting in a correspondingly large number of published PCRs, which often do not correspond with one another (Subramanian et al. 2012).

There have been additional standards issued that apply to the construction industry to promote greater comparability of the environmental performance of products. For example, ISO 21930 (ISO 2007) provided some guidance on both PCR and EPD development, but this was recently replaced by EN 15804 (CEN 2012) in Europe. EN 15804 is an integral PCR for building products and is considerably more detailed and prescriptive than ISO 14025; ISO 21930 is currently being revised. Different life cycle stages are divided into modules in EN 15804. Modules A1-A3 cover the production stage, A4-A5 the construction process, B1-B7 the use stage, and C1-C4 the end of life stage; beyond this is the 'after-life' stage (D). These are listed in Table 1 below. The publication of this standard ensures harmonization of core PCRs for building products in Europe (a core PCR is the basic PCR for a whole product group, upon which more specific PCRs are based). It is mandatory to report stages A1-A3, whereas the other stages are included for any reporting beyond cradle to factory gate.

Table 1. List of information modules within the product life cycle listed in CEN standard EN 15804 (CEN 2012).

Module	Life cycle stage	Description
A1	Production	Raw material supply
A2	Production	Transport
A3	Production	Manufacturing
A4	Construction	Transport
A5	Construction	Construction/installation
B1	Use	Use
B2	Use	Maintenance
B3	Use	Repair
B4	Use	Replacement
B5	Use	Refurbishment
B6	Use	Operational energy use
B7	Use	Operational water use
C1	End of life	De-construction/demolition
C2	End of life	Transport
C3	End of life	Waste processing
C4	End of life	Disposal
D	Beyond building life cycle	Reuse/recovery/recycling

The primary purpose of an EPD, according to ISO 14025, is to improve business to business (b2b) communication, but an EPD may also be used for business to consumer (b2c) communication. In the latter case, there are further requirements within the process, which particularly apply to verification procedures. In any case, ISO 14025 encourages those involved in the production of an EPD to take account of the level of awareness of the target audience. Standards are increasingly removing the flexibility (and uncertainty) that was once associated with determining the environmental performance of products and services. This should make it much easier to compare the environmental impacts of products within a product category in the future. Namely, EPD is presenting the life cycle of a product in a report, focusing on the product's environmental impacts, such as contributions to global warming, ozone depletion, water pollution, ozone creation, and greenhouse gas emissions. An EPD can include additional impacts that are of interest to the discloser, such as human toxicity, risk, and corporate social responsibility.

What is required is a standardized method of reporting environmental burdens associated with a specific functional unit, which has led to the development of product category rules (PCRs). These PCRs have been developed by different organizations, which have set up EPD programs; examples in Europe include the International EPD® system based in Sweden and the Institut Bauen und Umwelt based in Germany. Since the introduction of ISO 14025, there has been a proliferation of EPD systems, with their own PCRs. ISO 14025 encourages the operators of EPD programs to harmonize their methods and PCRs. In Europe, this has resulted in the creation of 'ECO', a platform for rationalizing EPDs, involving 11 EPD operators across Europe. This platform involves mutual recognition of EPDs and the creation of common PCRs, working from agreed core PCRs, such as EN 15804 in the built environment.

In theory, the introduction of EPDs using common PCRs suggests it should be possible to compare different building materials in terms of environmental impact. However, while it may be possible to make choices based on the environmental impacts associated with the manufacture of products, the use phase and end of life phase also need to be considered to understand the whole picture. Important considerations when examining the environmental consequences of the use of different materials must include the service life of the product, maintenance requirements, and performance in service, especially with regard to the impact on the operating energy of the building. This may require assumptions to be made regarding life span, maintenance, end of life scenarios, etc., which will have a critical impact upon the outcome of the LCA.

Although the use of EPDs has become somewhat standardized, concerns arise regarding Product Environmental Footprints (PEFs). The EU Commission published Product Environmental Footprint methods as part of the communication entitled 'Building the Single Market for Green Products' (2013/179/EU). These methods build on existing LCA methodologies and aim to harmonize them for greater comparability between products and services by defining methods, thereby reducing flexibility. This is precisely why EPDs were introduced and the need for yet another method of comparing the environmental footprints of products has been questioned (Finkbeiner 2014).

4 Harvested Wood Products and Atmospheric Carbon Storage

The claim that carbon benefits result from the use of wood products in the built environment depends on whether embodied emissions are lower than the amount of atmospheric carbon stored in the wood product itself. An embodied emission is an emission that is associated with the production of a product, e.g. the CO₂ eq. emissions associated with transport, production of electricity used for the sawing and planing of a wood product, the CO₂ emissions associated with the use of gas for heating of the kilns, etc. Pingoud and Lehtilä (2002) studied wood products in a Finnish context and estimated that GHG emissions associated with processing were equivalent to only 7% of the CO₂ equivalents stored in sawn wood products. These percentages rise with the amount of processing that is required for the wood product and are highest for virgin paper products (30-60%), but even in these extreme cases the amount of CO₂ equivalents released is lower than the amount stored in the product.

The advantages of using timber and other bio-derived materials as a means of storing sequestered atmospheric carbon in the built environment has also received considerable attention in the scientific literature (e.g., Brunet-Navarro et al. 2016, Jasinevičius et al. 2015, Pilli et al. 2015,). Although the environmental benefits of using natural materials, such as timber, in construction can be clearly demonstrated, the same cannot always be said for the economic benefits, unless the external costs of climate change are internalized in material prices. Doing so will require the development of carbon accounting methods (Sathre and Gustavsson 2009).

Numerous studies have demonstrated the benefits of using wood in the built environment as a long term carbon store (e.g., Hill 2011, Nepal et al. 2016). Yet, the role of harvested wood products in mitigating greenhouse gas emissions has only recently been recognized by the Kyoto Protocol. In 2009, during the 15th Conference of the Parties (COP 15) to the United Nations Framework Convention on Climate Change in Copenhagen, members agreed that harvested wood products (HWPs) could be included as an additional carbon pool. During the first commitment period (2008-2012), it was assumed that the quantity of carbon leaving the HWP pool each year

was equal to the annual inflow. This means that although a substantial quantity of atmospheric carbon may be stored in the HWP pool, this amount is assumed to be stable over time, thus negating net benefits in terms of mitigation potential. For the second commitment period (2013–2020), carbon accounting included carbon stock changes in the HWP pool.

Although the Intergovernmental Panel on Climate Change (IPCC) recognizes the importance of the built environment, its mitigation strategies included in the fourth and fifth assessment reports (IPCC 2007, 2014) are almost exclusively concerned with energy consumption. The use of wood as an example of a low embodied energy material is mentioned, but consideration of the potential for timber and other plant derived products to act as carbon stores in the built environment is lacking. Furthermore, the use of mitigation strategies associated with forestry is only connected to bioenergy and do not discuss the carbon storage potential of timber products. However, in 2009, the 14th Conference of the Parties (COP 14) did recognize the importance of including timber products as carbon sinks. Likewise, the 2011 Durban and 2012 Doha conferences stated that carbon stored in wood products should be integrated into reporting procedures.

Nevertheless, the benefits of using wood products as a store for atmospheric carbon dioxide are only realized if the products have a sufficiently long life. The question of the temporal nature of carbon emissions into the atmosphere and considerations of the length of time that atmospheric carbon is held in storage are extremely important when biogenic carbon is considered (Cherubini et al. 2012). Unfortunately, there is no consensus regarding the methodology for measuring and accounting for carbon in biogenic products. Although the ILCD methodology is still utilized, there have not been any useful developments in standardization. The 2008 version of PAS2050 (BSI 2008) initially included methods for calculating the temporal aspects of biogenic carbon storage in annex C, but by the time the 2011 version was published, the methods were no longer included. Similarly, the European Standard EN 16485 (CEN 2014) that designated product category rules for round and sawn timber featured a temporal calculation method for determining the storage of biogenic carbon in its draft form, but not in the final publication.

Section 5.4.9 in the current version of the PEF guidance document, Commission Recommendation 2013/179/EU (European Commission, 2013), available from the European Commission, deals with the issue of temporary carbon storage, stating, “Credits associated with temporary (carbon) storage or delayed emissions shall not be considered in the calculation of the default EF impact categories. However, these may be included as ‘additional environmental information.’”

Conventional LCA methods do not assign any benefits to the temporary storage of atmospheric carbon because the timing of emissions relative to removal is disregarded (Pinsonnault et al. 2014). Although there are benefits to be gained from using timber products in long life products as a store of atmospheric carbon, there is still no recognized way of accounting for this (Brandão et al. 2013).

5 Life Cycle Assessments of Organizations

The O-LCA approach is a compilation and evaluation of the inputs, outputs, and potential environmental impacts of the activities associated with an organization. The organization, which is the object studied in O-LCA, is defined by ISO/TS 14072 (ISO 2014). It can be a person or a group of people. O-LCA can be performed by an organization of any size and sector.

The organization’s portfolio usually includes more than one product. When performing an O-LCA, all activities associated with the set of goods and services an organization provides are assessed at the same time. Therefore, an O-LCA can be incredibly complex. UNEP/SETAC (2015) published *Guidance on Organizational Life Cycle Assessment*, which summarizes opportunities an O-LCA could provide. An organization may be motivated to perform an O-LCA for analytical, managerial, or societal reasons. Examples of analytical goals include: to understand internal operations, identify the operations with highest impacts on the environment, identify the risks and define the activities to reduce the impacts, etc. Managerial objectives may include: gain support for strategic decisions, improve organizational procedures, initiate environmental communication and reporting with stakeholders, reduce operational costs, and/or demonstrate environmental awareness for marketing purposes.

These goals may encourage other organizations and foster sustainable development of society. However, the objectives and/or justification for LCA should be adapted to each organization. The ISO/TS 14072 (ISO 2014) does not allow the use of O-LCA for comparative purposes. Unlike a product LCA, an O-LCA is not capable of providing comparative assertions to be disclosed to the public. Most principles, requirements, and guidelines of a product LCA apply to an O-LCA. An O-LCA requires the definition of two new elements, roughly equivalent to the functional unit and reference flow, the so-called reporting organization and reporting flow.

Martínez-Blanco et al. (2015a) compared the LCA of products and the O-LCA to identify the main differences in the scope phase of LCA analysis. The authors found that the characterization of the organization must be evaluated carefully. The characterization of the so-called reporting organization should include three elements: name and description of the organization under study (i.e., whole organization or part of it), definition of the consolidation method (i.e., which sites should be considered), and the reference period to be considered in the O-LCA. Additionally, the system boundary of the study should define which direct and indirect activities are to be included. In the O-LCA, all relevant upstream activities and downstream burdens should be incorporated.

Witczak et al. (2014) conducted evaluations of the implementation of LCA in small and medium-sized enterprises (SMEs) by investigating 46 Polish companies. The study concluded that SMEs should see the economic benefits of proposed environmental improvements and, therefore, LCA should be performed simultaneously with Life Cycle Costing (LCC). Furthermore, the analyses led to the conclusion that incentives for SMEs to take measures should come from outside the organization, such as requirements for green public procurements, or as part of an assessment made by suppliers within the supply chain. In the *Guidance on Organizational Life Cycle Assessment* (UNEP/SETAC 2015), the first practical experiences of approaches encompassing O-LCA are identified. Eleven case studies of the so-called "First Movers" are included in the guidance document to illustrate some methodological facets and benefits that the methodology could bring to organizations. Most of these organizations developed their own adapted methodology. Eight sectors, including hotel and catering, food, chemical, car manufacturing, energy, retail,

consulting, and cosmetic and personal care, and four regions, including South and North America, Europe, Asia, and Oceania, were represented in the case studies. BASF, a chemical company, was included as a pilot project. Their industrial complex is located in the Demarchi neighborhood of São Bernardo do Campo, Brazil and includes seven production plants, mainly dedicated to paint and varnish production. The goal of the study was to evaluate the environmental impacts of production systems over time to evaluate impact trends and to identify relevant effects on impact distribution due to changes in production units. Therefore, the cradle-to-gate boundary approach was used. The reference unit was 1 tonne of finished product. Primary data, including the organization's annual production reports for 2010, 2011, and 2012, and secondary data, including technical literature, research reports, and LCA databases, were used in the study. The impact assessment included raw materials and energy consumption across the following impact categories:

- depletion of natural resources,
- cumulative energy consumption,
- human toxicity potential,
- land use,
- emissions (e.g., gaseous emissions, global warming potential, photochemical ozone creation potential, ozone depletion potential, and acidification potential),
- liquid emissions (volume of wastewater), and
- solid emissions (the inventory flow waste generated)).

To the best of our knowledge, no O-LCA has yet been performed for the forest products sector.

Besides the O-LCA, the so-called social organizational LCA (SO-LCA) has also been proposed (Martínez-Blanco et al. 2015b). The SO-LCA is presented as a method able to boost the social life cycle assessment (S-LCA), which addresses social aspects from a life cycle perspective. An S-LCA is a method that can be used to assess the social and sociological aspects of products as well as their actual and potential positive and negative impacts along the life cycle. This method looks at the extraction and processing of raw materials, manufacturing, distribution, use, reuse, maintenance, recycling, and final disposal. S-LCA makes use of generic and site-specific data, can be quantitative, semi-quantitative or qualitative, and

complements the environmental LCA and LCC (UNEP/SETAC 2009). The UNEP *Guidelines for Social Life Cycle Assessment of Products* discusses the main difference between the environmental LCA and social S-LCA as well as limitations of S-LCA, due to the complexity of the social dimension. The S-LCA methodology proposes 189 indicators of impacts, among which only 8 refer to the product level, while 127 refer to the organizational level and 69 refer to the country level. Identified challenges of the S-LCA were addressed by Martínez-Blanco et al. (2015b). The difficult challenge of linking social indicators to the product could be overcome in the SO-LCA by linking social indicators to the reference unit of the SO-LCA (e.g., the reporting organization), instead of the product(s). Problems surrounding data collection and missing data in the S-LCA, which is generally comprised only of generic sector or country data, could be resolved by the SO-LCA, as specific data is more likely to be available on the organization than on the product level. Furthermore, the application and applied use of the S-LCA, which is not clearly defined and does not adequately evaluate social performance on the product level, could be overcome by the SO-LCA, which refers to the assessment of organizational behavior and performance.

6 Discussion

The use of life cycle thinking and various LCA methodologies could bring direct and indirect benefits to enterprises in the forest product sector. These approaches could be included in organizations' decision-making processes to create value. Typically, organizations focus on processes within their own organization, such as labor costs, manufacturing, and logistics. Adding resource use assessments in their product life cycle across the entire value chain could reduce costs and provide additional benefits.

An assessment of the whole value chain is a data intensive process but delivers a product's environmental impacts across the value chain, from product development, sourcing, manufacturing, distribution, marketing, use, and reuse or disposal. Energy, water, and raw material use involve real costs that, with proper handling, can reduce environmental impacts across the value chain. Assessing the end-to-end product life cycle opens the largest potential opportunities for additional value creation through cost reduction and/or improved reputation.

Why isn't the forest products sector implementing LCA to a greater extent? The timber sector is an unusual industrial sector, as it is made up of a very large number of relatively small enterprises. This is partly due to the geographical distribution of forests and partly to the often local nature of the supply chain. Forest product companies do not see the need to invest in the expensive LCA, which can involve quite invasive questions about products and processes. This problem can, in part, be addressed by the development of generic EPDs, which cover certain product types for an entire sector and can be produced by member organizations. Nevertheless, larger companies within the sector do see the need for conducting LCAs, mostly due to competition for other materials, and a considerable number of EPDs have been produced over the past five years (Hill and Dibdiakova 2016).

Organizations in the forest products sector should use the O-LCA to reveal environmental hotspots where the organization should focus energies and intervention, throughout the value chain and among all products and operations involved in the provision of the portfolio. Furthermore, by understanding risk and impact reduction, opportunities could be a basis for strategic decisions at different levels. These decisions could be based on technologies, investments, and new product lines. O-LCA may also serve as a framework for tracking environmental performance over time and for informing corporate sustainability reporting. In many respects, the forest products sector is taking the lead in social and environmental reporting with the long-established use of certification schemes. Many of these have been voluntary, but an increasing emphasis has been placed on legislation. The European Parliament introduced the Sixth Community Action Programme in July 2002 to deal with the trade in illegally harvested wood. Subsequently, there was a report produced by the European Commission entitled the 'Forest Law Enforcement, Governance and Trade (FLEGT): Proposal for an EU Action Plan.' The European Union then negotiated Voluntary Partnership Agreements (FLEGT VPAs) with timber producing countries in order to introduce a licensing scheme to regulate trade. This was only partially successful and consequently the EU Timber Regulation came into force in December 2010, making it against the law to place illegally harvested timber and timber products on the EU market as of 3rd March 2013. The trend is increasingly moving towards

the development of robust chains of custody throughout the entire value chain and the move from voluntary to legislated certification schemes. The chain of custody schemes that are required can be extended beyond the sawmill gate and involve all stages of the life cycle, which can also potentially allow for the tracking of sequestered carbon, as well as environmental burdens.

There has been an increasing number of timber EPDs appearing. In March 2011, the Construction Products Regulation (305/2011) was introduced, replacing the Construction Products Directive (89/106/EEC). The Construction Products Regulation states that where a European standard exists, it must take precedence. In addition, it states, "for the assessment of the sustainable use of resources and of the impact of construction works on environment Environmental Product Declarations should be used when available," (EU Regulation 2011). An increasing emphasis will be placed on environmental and social credentials by specifiers in the built environment and it is important that the forest products sector has the required information. Architects are increasingly using building information modelling (BIM) software, which will likely incorporate environmental and social impact information in the future, alongside the physical material properties that are already embedded.

The forest-based sector can make a significant contribution towards the mitigation of climate change caused by anthropogenic CO₂ emissions, reduced energy consumption, increased wood products recycling, and reuse. Apart from these environmental benefits, the use of forest products in long life products in the built environment, allows for the prolonged storage of atmospheric carbon dioxide. Wood modification (chemical, thermal, impregnation) is being increasingly used in the wood products sector, but there is relatively little information on the environmental impacts of the processes. This is being addressed by COST Action FP1407 "Understanding wood modification through an integrated scientific and environmental impact approach," where researchers from 36 countries are collaborating on the development of technologies and analyzing their environmental impacts. This requires analysis of the whole value chain, from forest through processing, installation, in-service, end of life, second/third life (cascading), and ultimately incineration with energy recovery (Sathre and Gustavsson 2006). The creation of an LCA is a very complex process and is not always something which is easily undertaken by small

enterprises. By participating in research communities, such as COST Action FP1407, the entire sector can come together to participate in collecting and analyzing data for the benefit of all.

7 Conclusions

LCA is a useful tool for reporting on the environmental burdens associated with a product or process and is increasingly being used to back up environmental claims, especially with the use of Environmental Product Declarations. The forest products sector must be prepared to meet the challenges of the future. The timber sector has a good story to tell, but other sectors with more resources at their disposal are not standing still. A very important benefit of using timber from sustainable sources in long life products is the storage of sequestered atmospheric carbon dioxide. Unfortunately, at the time of writing, the situation regarding the methodology of measuring and accounting for carbon in biogenic products is lacking. With current global efforts regarding the mitigation and adaptation of greenhouse gas emissions, the importance of including the methods for determining the storage of biogenic carbon is becoming increasingly important. The forest products sector should act globally and collectively pursue this.

8 References

- Audenaert, A., De Cleyn, S.H. & Buyle, M. 2012. LCA of low-energy flats using the Eco-indicator 99 method: Impact of insulation materials. *Energy and Buildings*, 47, pp.68-73.
- Ayres, R.U. 1995. Life cycle analysis: A critique. *Resources, Conservation and Recycling*, 14(3), pp.199-223.
- Bare, J.C., Hofstetter, P., Pennington, D.W. & De Haes, H.A.U. 2000. Midpoints versus endpoints: The sacrifices and benefits. *The International Journal of Life Cycle Assessment*, 5(6), pp.319-326.
- Brandão, M., Levasseur, A., Kirschbaum, M.U., Weidema, B.P., Cowie, A.L., Jørgensen, S.V., Hauschild, M.Z., Pennington, D.W. & Chomkham Sri, K. 2013. Key issues and options in accounting for carbon sequestration and temporary storage in life cycle assessment and carbon footprinting. *The International Journal of Life Cycle Assessment*, pp.1-11.
- Brankatschk, G. & Finkbeiner, M. 2014. Application of the Cereal Unit in a new allocation procedure for agricultural life cycle assessments. *Journal of Cleaner Production*, 73, pp.72-79.
- Brunet-Navarro, P., Jochheim, H. & Muys, B. 2016. Modelling carbon stocks and fluxes in the wood product sector: A comparative review. *Global Change Biology*, 22(7), pp.2555-2569.
- BSI. 2008. Specification for the assessment of the life cycle greenhouse gas emissions of goods and services. BSI British Standards. ISBN, 978(0), pp.580.
- CEN. 2012. EN 15804: Sustainability of construction works – Environmental product declarations – Core rules for the product

- category of construction products. Brussels: CEN.
- CEN. 2014. EN 16485: Round and sawn timber – Environmental Product Declarations – Product category rules for wood and wood-based products for use in construction. Brussels: CEN.
- Chau, C.K., Leung, T.M. & Ng, W.Y. 2015. A review on life cycle assessment, life cycle energy assessment and life cycle carbon emissions assessment on buildings. *Applied Energy*, 143, pp.395-413.
- Cherubini, F., Guest, G. & Strømman, A.H. 2012. Application of probability distributions to the modeling of biogenic CO₂ fluxes in life cycle assessment. *Global Change Biology - Bioenergy*, 4(6), pp.784-798.
- De Haes, H.A.U. 1993. Applications of life cycle assessment: expectations, drawbacks and perspectives. *Journal of Cleaner Production*, 1(3-4), pp.131-137.
- Del Borghi, A. 2013. LCA and communication: Environmental product declaration. *The International Journal of Life Cycle Assessment*, pp.1-3.
- Ding, G.K. 2008. Sustainable construction—The role of environmental assessment tools. *Journal of Environmental Management*, 86(3), pp.451-464.
- Dong, Y.H. & Ng, S.T. 2014. Comparing the midpoint and endpoint approaches based on ReCiPe - A study of commercial buildings in Hong Kong. *The International Journal of Life Cycle Assessment*, 19(7), pp.1409.
- Ehrenfeld, J.R. 1997. The importance of LCAs—warts and all. *Journal of Industrial Ecology*, 1(2), pp.41-49.
- EU Regulation. 2011. No 305/2011 of the European Parliament and of the Council of 9 March 2011 laying down harmonised conditions for the marketing of construction products and repealing Council Directive 89/106/EEC.
- European Commission (EC). 2013. Product Environmental Footprint Guide [PEF Guide] Annex II of Commission Recommendation of 9 April 2013 on the use of common methods to measure and communicate the life cycle environmental performance of products and organisations (2013/179/EU). Official Journal of the European Union, L124(4.5.2013), pp. 6-210.
- Finkbeiner, M. 2014. Product environmental footprint—breakthrough or breakdown for policy implementation of life cycle assessment? *International Journal of Life Cycle Assessment*, 19, pp.266-271.
- Finveden, G. 2000. On the limitations of life cycle assessment and environmental systems analysis tools in general. *The International Journal of Life Cycle Assessment*, 5(4), pp.229-238.
- Finveden, G., Hauschild, M.Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D. & Suh, S. 2009. Recent developments in life cycle assessment. *Journal of Environmental Management*, 91(1), pp.1-21.
- Forsberg, A. & Von Malmborg, F. 2004. Tools for environmental assessment of the built environment. *Building and Environment*, 39(2), pp.223-228.
- Frischknecht, R. & Stucki, M. 2010. Scope-dependent modelling of electricity supply in life cycle assessments. *The International Journal of Life Cycle Assessment*, 15(8), pp.806-816.
- Gala, A.B. & Rauegi, M. 2015. Introducing a new method for calculating the environmental credits of end-of-life material recovery in attributional LCA. *The International Journal of Life Cycle Assessment*, 20(5), p.645.
- Hauschild, M.Z., Goedkoop, M., Guinée, J., Heijungs, R., Huijbregts, M., Jolliet, O., Margni, M., De Schryver, A., Humbert, S., Laurent, A. & Sala, S. 2013. Identifying best existing practice for characterization modeling in life cycle impact assessment. *The International Journal of Life Cycle Assessment*, pp.1-15.
- Hill, C.A., 2011. An introduction to sustainable resource use. Earthscan, Routledge.
- Hill, C.A.S. & Dibdiakova, J. 2016. The environmental impact of wood compared to other building materials. *International Wood Products Journal*, 7(4), pp.215-219.
- IPCC. 2007. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland, 104 pp.
- IPCC. 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.
- ISO. 2006a. ISO 14040—Environmental management—Life cycle assessment—Principles and framework. International Organisation for Standardization, Geneva, Switzerland.
- ISO. 2006b. ISO 14044—Environmental management—Management—Life cycle assessment—Requirements and guidelines. International Organisation for Standardization, Geneva, Switzerland.
- ISO. 2006c. ISO 14025—Environmental labels and declarations—Type III environmental declarations—Principles and procedures. International Organisation for Standardization, Geneva, Switzerland.
- ISO. 2007. ISO 21930—Sustainability in building construction—Environmental declaration of building products. International Organisation for Standardization, Geneva, Switzerland. ISO. 2014.
- ISO. 2014. ISO/TS 14072—Environmental management—Life cycle assessment. —Requirements and guidelines for organizational life cycle assessment. International Organisation for Standardization, Geneva, Switzerland.
- Jasinevičius, G., Lindner, M., Pingoud, K. & Tykkylainen, M. 2015. Review of models for carbon accounting in harvested wood products. *International Wood Products Journal*, 6(4), pp.198-212.
- Jungmeier, G., Werner, F., Jarnehammar, A., Hohenthal, C. & Richter, K. 2002. Allocation in LCA of wood-based products experiences of cost action E9. *The International Journal of Life Cycle Assessment*, 7(6), pp.369-375.
- Krozer, J. & Vis, J.C. 1998. How to get LCA in the right direction? *Journal of Cleaner Production*, 6(1), pp.53-61.
- Martínez-Blanco, J., Lehmann, A., Chang, Y.J. & Finkbeiner, M. 2015a. Social organizational LCA (SOLCA) — a new approach for implementing social LCA. *The International Journal of Life Cycle Assessment*, 20(11), pp.1586.
- Martínez-Blanco, J., Inaba, A. & Finkbeiner, M. 2015b. Scoping organizational LCA—challenges and solutions. *The International Journal of Life Cycle Assessment*, 20(6), pp.829.
- Monteiro, H. & Freire, F. 2012. Life-cycle assessment of a house with alternative exterior walls: comparison of three impact assessment methods. *Energy and Buildings*, 47, pp.572-583.
- Nepal, P., Skog, K.E., McKeever, D.B., Bergman, R.D., Abt, K.L. & Abt, R.C. 2016. Carbon mitigation impacts of increased softwood lumber and structural panel use for nonresidential construction in the United States. *Forest Products Journal*, 66(1), pp.77-87.

- Ortiz, O., Castells, F. & Sonnemann, G. 2009. Sustainability in the construction industry: A review of recent developments based on LCA. *Construction and Building Materials*, 23(1), pp.28-39.
- Pilli, R., Fiorese, G. & Grassi, G. 2015. EU mitigation potential of harvested wood products. *Carbon Balance and Management*, 10(1), pp.6.
- Pingoud, K. & Lehtilä, A. 2002. Fossil carbon emissions associated with carbon flows of wood products. *Mitigation and Adaptation Strategies for Global Change*, 7(1), pp.63-83.
- Pinonnault, A., Lesage, P., Levasseur, A. & Samson, R. 2014. Temporal differentiation of background systems in LCA: relevance of adding temporal information in LCI databases. *The International Journal of Life Cycle Assessment*, 19(11), pp.1843-1853.
- Sala, S., Vasta, A., Mancini, L., Dewulf, J. & Rosenbaum, E. 2015. Social life cycle assessment: State of the art and challenges for supporting product policies. EUR 27624 EN.
- Sathre, R. & Gustavsson, L. 2006. Energy and carbon balances of wood cascade chains. *Resources, Conservation and Recycling*, 47(4), pp.332-355.
- Sathre, R. & Gustavsson, L. 2009. Using wood products to mitigate climate change: External costs and structural change. *Applied Energy*, 86(2), pp.251-257.
- Subramanian, V., Ingwersen, W., Hensler, C. & Collie, H. 2012. Comparing product category rules from different programs: Learned outcomes towards global alignment. *The International Journal of Life Cycle Assessment*, pp.1-12.
- UNEP/SETAC. 2009. Guidelines for social life cycle assessment of products. Life-Cycle Initiative, United Nations Environment Programme and Society for Environmental Toxicology and Chemistry., Paris, France. http://www.unep.fr/shared/publications/pdf/DTIx1164xPA-guidelines_sLCA.pdf (Accessed April 15, 2016).
- UNEP/SETAC. 2015. Life Cycle Initiative—Guidance on organizational life cycle assessment. United Nations Environment Programme. Paris, France. http://www.lifecycleinitiative.org/wp-content/uploads/2015/04/o-lca_24.4.15-web.pdf (Accessed April 15, 2016).
- Witczak, J., Kasprzak, J., Klos, Z., Kurczewski, P., Lewandowska, A. & Lewicki, R. 2014. Life cycle thinking in small and medium enterprises: The results of research on the implementation of life cycle tools in Polish SMEs—Part 2: LCA related aspects. *The International Journal of Life Cycle Assessment*, 19(4), pp.891.