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Life cycle assessment (LCA) of wood-based building materials

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Abstract: In this chapter we discuss major issues regarding life cycle assessment (LCA) and environmental performance analysis of wood-based building materials. We follow the life cycle of a wood product, beginning with a discussion of sustainable forestry and the growth of trees. We then discuss the processes of manufacturing wood-based building products, focusing on issues of adhesives and preservatives. We discuss the design and construction of buildings and infrastructure made of wood, with an emphasis on eco-design processes. We describe the system-wide material and energy flows associated with wood-based construction in a life cycle perspective, and discuss the climate benefits of using wood material from sustainably managed forests.

Key words: wood-based products, life cycle assessment, forestry, eco-design, climate change mitigation.

14.1 Introduction

14.1.1 Wood products and a vision of sustainability

A great challenge for humankind is to transition to a sustainable society. Such a society will require the use of renewable materials, coupled with large reductions in the overall use of natural resources and in environmental impacts including greenhouse gas (GHG) emissions. The built environment is a key sector in meeting this challenge, due to its large use of natural resources and primary energy and its significant impacts on the environment. In Europe, for example, the built environment accounts for about 42% of energy use and produces 35% of total GHG emissions (EC, 2007). Understanding and improving the environmental profile of the materials used in the construction sector is essential to reducing the environmental impact of the built environment.

Wood is an inherently renewable material that is produced through natural processes in forest ecosystems. The life cycle of wood building materials includes the growth of trees, the harvest and processing of woody biomass, the manufacture and assembly of wood-based products, the utilisation and maintenance of the building, and the disassembly and end-of-life management of the wood material (Yaro, 1997). When trees are harvested from a sustainably managed forest, new trees re-grow in their place, providing a renewable source of biomass feedstock. As part of a continuous cycle of material flow, use of wood products avoids the build-up of waste materials from manufacturing or disposal, as the biomass residues can be used as a source of bioenergy. Wood products have the potential to play a major role in the development of a sustainable built environment, particularly through the integration of material and energy flows in the construction sector with those in the forestry, energy, industrial and waste management sectors.

14.1.2 Life cycle assessment (LCA) of wood-based building materials

A growing concern about the environmental effects of the production and use of goods, as well as about how goods are disposed of at the end of their service life, has led to increasing interest in wood-based products made in a sustainable environmental manner. Long-term sustainable development is a key concern in many countries, giving rise to regulations regarding the impact of products during their life cycle, including the commitment to create effective reverse logistics strategies to manage post-use materials. Improved knowledge of the environmental impacts of the materials and processes associated with productive sectors including the wood-based sector is a key factor in guiding efforts towards green production processes and green markets (Bovea and Vidal, 2004).

Life cycle assessment (LCA) is a tool to assess the environmental impact of materials, products and services, and should contribute to the decision-making process towards sustainability (Baumann and Tillman, 2004). The LCA methodology has been applied to a wide range of processes and sectors. Specific to the wood products sector, numerous studies have been carried out to investigate the environmental performance of wood-based products destined for different uses such as floor coverings (Jönsson *et al.*, 1997; Petersen and Solberg, 2003; Nebel *et al.*, 2006), window frames (Richter and Gugerli, 1996; Salazar and Sowlati, 2008), particleboard (Rivela *et al.*, 2006), medium density fibreboard (Rivela *et al.*, 2007), hardboard (González-García *et al.*, 2009b), furniture (Taylor and van Langenberg, 2003), goods containers (González-García *et al.*, 2011a), paper pulp (González-García *et al.*, 2009c, 2011b), wall assemblies (Werner, 2001; Lippke and Edmonds, 2006), and packaging materials (Farreny *et al.*, 2008). Other studies have analysed complete buildings rather than building components, including single-family houses (Buchanan and Honey, 1994; Scharai-Rad and Welling, 2002; Lippke *et al.*, 2004) and apartment buildings (Börjesson and

Gustavsson, 2000; Gustavsson *et al*., 2006b; Gustavsson and Sathre, 2006; John *et al*., 2009; Gustavsson *et al*., 2010). These studies have aimed to document the overall environmental performance of the wood-based products, as well as identify the processes with the highest contributions to environmental impact. Differences among LCA studies of wood-based products concern, for example, the system boundaries of the analysis (cradle-to-gate or cradle-to-grave) and the life cycle inventory data (primary or secondary data).

The LCA methodology allows not only the quantification of current environmental profiles but also the identification of improvement potentials in order to reduce future environmental impacts. LCA studies typically identify the most important contributors to the environmental impacts, which allows focused effort on reducing those impacts. End-of-life management of wood-based products is found to be an important factor in energy and GHG balances. Recovery of the post-use material for use as bioenergy is beneficial, while disposal in landfills typically causes greater impacts. Forest activities to produce roundwood (the main raw material in wood-based products) may also be an environmental hot spot due to their contribution to impact categories such as acidification, eutrophication, and formation of photochemical oxidants. The application of agrochemicals and use of forest machinery powered by fossil fuels are the main contributors in this area. Another hotspot involves activities related to processing of wood into wood-based panels (e.g., production of fibreboard) due to the use of petroleum-based resins such as urea- and phenol-formaldehyde. Nevertheless, a general conclusion of comparative studies of wood-based vs. non-wood materials is that wood products from sustainably managed forests have the potential to produce significantly less life cycle environmental impact than other common building materials such as concrete and steel (Werner and Richter, 2007; Sathre and O'Connor, 2010a).

In this chapter we discuss major issues regarding LCA and environmental performance of wood-based building materials. We follow the life cycle of a wood product, beginning with a discussion of forestry and the growth of trees. We then focus on the processes of manufacturing a wood-based building product, followed by a discussion of environmentally compatible design and building with wood. We then describe system-wide material and energy flows associated with wood-based construction, and discuss the climate benefits of using wood material from sustainably managed forests.

14.2 Forestry and wood production

The life cycle of a wood product begins with the germination of a tree seed, and continues through the growth and harvest of the tree and the manufacture and use of the product. Consideration of forest ecosystems is essential to accurately understand the eco-efficiency of wood product use. In contrast to other building materials, such as steel and concrete that are manufactured through technological processes in human-made factories, wood is produced through natural biological processes occurring in growing trees. The process of photosynthesis, powered by solar energy captured by tree leaves, produces sugars from carbon dioxide taken from the air and water taken from the soil. These sugars are converted by the trees into complex organic molecules such as cellulose, hemicellulose and lignin, which combine in a composite matrix to form wood. The wood material that is produced organically by living trees can then be harvested and processed into various types of construction products. Meaningful environmental assessment of a wood-based product generally requires that the wood be sourced from sustainable forestry. Forests managed for timber production are typically considered sustainable if the harvests remove no more wood than is grown, i.e., if the landscape-level forest inventory is not declining over time (Lippke *et al.*, 2011). Forests managed for sustainable multiple use attempt to include a balance between timber output, ecosystem services, and social values, acknowledging that not all forests can fulfil all needs.

Globally, about 31% of total land area is covered by forests, corresponding to a forest area of just over 4 billion hectares (FAO, 2010). More than half of the total forest area is in five countries: Russia, Brazil, Canada, USA and China. At the global level, forest area decreased at a rate of about 5.2 million hectares per year during the period 2000 to 2010, down from an estimated 8.3 million hectares per year during the period 1990 to 2000. This decrease in forest area is the net result of two opposing processes: deforestation, occurring at a rate of about 13 million hectares per year during the period 2000 to 2010 (down from about 16 million hectares per year in the 1990s), and afforestation and natural expansion of forests in other areas. Most of the loss of forest currently occurs in tropical regions, particularly in Africa and South America. Most of the increase in forest area occurs in the temperate and boreal zones, as well as in some emerging economies. In Europe, net forest area increased by about 700,000 hectares per year during the period 2000 to 2010, as a result of new forest planting and natural expansion of forests onto former agricultural land. In North America, forest land area has been quite stable in recent decades. In China, large-scale afforestation efforts have increased the forest area by an average of 3 million hectares per year during the period 2000 to 2010.

The quantity and quality of wood biomass produced in a forest can be significantly influenced by forest management activities. A continuum of forest management intensities is possible, from an intense plantation regime involving species selection and nutrient management to the non-management and non-use of forests (Eriksson *et al.*, 2007; Poudel *et al.*, 2012). A complete

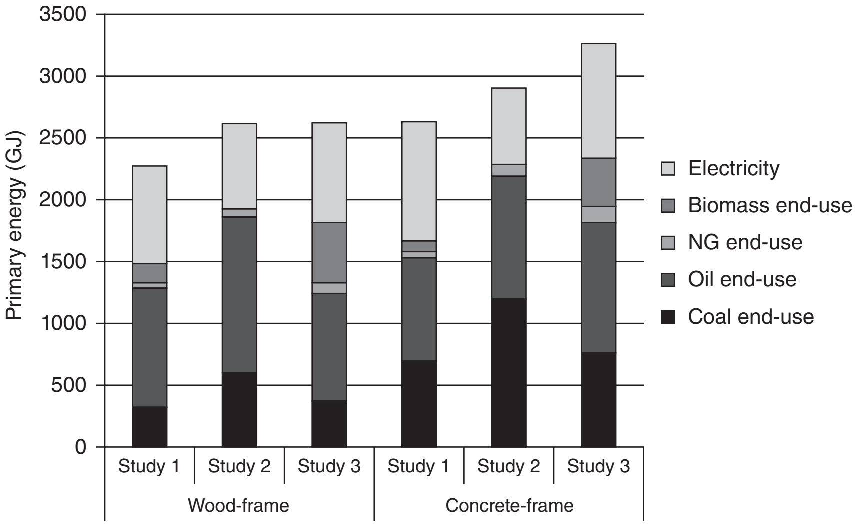
LCA of wood-based building materials will take into account the impacts resulting from forestry activities such as silvicultural operations, logging operations and secondary hauling (Berg and Lindholm, 2005; González-García *et al*., 2009a). In general, increasing the intensity of forest management results in greater production of biomass, though the return on management inputs tends to diminish as intensity increases. More intensive forest management, while producing marginally more environmental impact within the forest than less intensive management, may result in less overall impact due to the greater quantities of wood produced that can substitute for non-renewable materials and fuels (Eriksson *et al*., 2007; Sathre *et al*., 2010).

14.3 Wood product manufacture

14.3.1 Life cycle inventory data

Essential procedures in identifying and assessing the environmental impacts of wood-based product manufacturing systems include the definition of system boundaries, functional unit, and allocation methods, as well as the collection and processing of relevant life cycle inventory (LCI) data (ISO, 2006). Cradle-to-gate LCA studies cover all processes from natural resource extraction up to the factory exit gate, and exclude from assessment the product use and end-of-life management. Other studies employ a cradle-to-grave perspective including the maintenance of the product and post-use management such as recycling or disposal. The quality of LCI data is a key factor in the validity of the analysis, and adequate data must be used if the results are to be representative of the sector. LCAs of innovative products or processes will ideally use LCI data taken directly from field studies of production systems, which may be complemented with secondary data taken from databases. Variability in LCI data is inevitable, because different physical processes can be used to produce the same material, and each process has unique requirements and effects on the environment. The efficiency of industrial technologies has generally improved over time resulting in differences in energy requirements and emissions between materials processed by state-of-the-art technologies and those made in older facilities. Variation is also seen geographically, as technological innovations diffuse across countries and regions.

Data on industrial energy use can also vary depending on the methodology used to obtain the data. System boundaries of an energy analysis can range from a restrictive analysis of direct energy and material flows of a particular process, to an expansive analysis including energy and material flows of entire industrial chains and society as a whole (Boustead and Hancock, 1979). Data may be direct measurements of a particular machine



14.1 Primary energy used for production of materials for wood- and concrete-framed versions of a four-storey apartment building, using specific energy use data from three different process analyses. Study 1 is Fossdal (1995), Study 2 is Worrell *et al*. (1994) and Study 3 is Björklund and Tillman (1997) (adapted from Gustavsson and Sathre, 2004).

or factory, or may be aggregated for an entire industrial sector. As an illustration of such variability, Fig. 14.1 shows the primary energy used for producing materials for functionally equivalent versions of a four-storey apartment building made with a wood frame and a concrete frame, using specific energy use data from three different European process analyses. These results suggest that in spite of absolute differences between the analyses (due to varying system boundaries, regional differences, etc.), the *relative* energy use of wood vs. non-wood materials is more or less consistent (Gustavsson and Sathre, 2004).

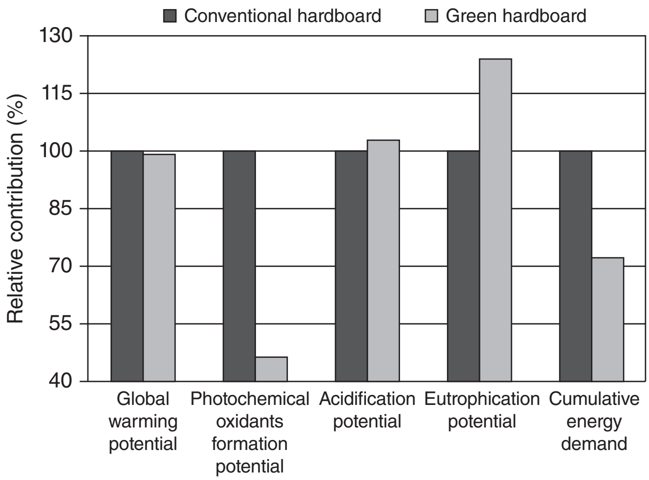
14.3.2 Wood adhesives: conventional and new green formulations

Distinctive characteristics of wood raw materials are its anisotropic and variable nature. Wood has different physical and mechanical properties in the longitudinal, radial, and tangential directions, due to different functional requirements within living trees. Furthermore, wood properties vary between tree species and climatic zones of origin, and within individual trees due to growth rings and knots. Traditionally, these factors were accommodated in building construction by conservative safety factors and by informed judgement of experienced woodworkers. More recently, these sources of performance variability are being overcome by the use of composite wood products, made by adhesively bonding together many smaller pieces of wood, thus creating a more homogeneous and predictable material. The individual wood elements can be of different sizes; examples include glue-laminated beams made from wooden boards, plywood panels made from thin wooden veneers, oriented strand board (OSB) made from strands of wood, particleboard made from flakes or particles of wood, and fibreboard made from individual wood fibres.

Composite wood products require the use of adhesives for bonding the wood elements. Typically, petroleum-based adhesives such as urea- or phenol-formaldehyde are used. The use of formaldehyde-based adhesives results in formaldehyde emissions derived from the production and end-use processes, resulting in negative environmental impacts (Imam *et al.*, 1999; US EPA, 2002). Environmental consequences of wood-based panel manufacture using conventional adhesives are documented in the literature (Rivela *et al.*, 2006, 2007; González-García *et al.*, 2009b). These studies found that the use of petroleum-based adhesive is an environmental hot spot that is responsible for pollutant emissions with significant contributions in impact categories including global warming, photochemical oxidants formation, acidification, eutrophication and toxicity. Evidently, potential environmental improvements are possible if these conventional adhesives are substituted by new green formulations.

Research in recent years has focused on reduction of adhesive use and on development of environmentally compatible adhesives. More natural and safer alternatives could be lignin-based materials (Moubarik *et al.*, 2009) such as lignosulfonates, organosolved lignin, kraft lignin, flavonoid-based tannins from certain trees (Widsten *et al.*, 2009), starch from renewable sources, or glues derived from animal tissue casein (Imam *et al.*, 1999). Widsten and Kandelbauer (2008) assessed the production of fibreboard using an adhesive based on lignin with enzymes, giving good results at lab and pilot scale. Moubarik *et al.* (2009) proposed the use of resins made from cornstarch and tannin from the quebracho tree (*Schinopsis balansae*) as an adhesive to partially substitute phenol-formaldehyde resin in plywood production. Panels with improved mechanical properties and water resistance, as well as lower formaldehyde emissions, were obtained and the environmental profile was improved.

Recent studies have documented the environmental benefits of using alternative adhesives instead of conventional petroleum-based adhesives. González-García *et al.* (2011d) studied hardboard production using a two-component bio-adhesive formulated with a wood-based phenolic material and a phenol-oxidising enzyme. Compared to conventional hardboard



14.2 Comparison of environmental profiles of conventional and green hardboard production processes.

manufacture using phenol-formaldehyde resin (González-García *et al.*, 2009b), significant environmental benefits were achieved in categories such as photochemical oxidants formation and cumulative energy demand, in a cradle-to-gate perspective (see Fig. 14.2). The highest benefits were reported in terms of photochemical oxidant formation, with reductions of up to 50%. The results indicated that the production of green hardboard using a green adhesive should be industrially viable, meeting the performance specifications of hardboard produced with conventional phenolic resin. However, special attention should be paid to the production of these adhesives, especially if the enzyme laccase is used in the composition, as the laccase production process is energy intensive which could limit the environmental benefits.

14.3.3 Wood decay and preservation

Wood is a biologically-produced material, and as part of natural material cycles can be decomposed by a variety of organisms such as fungi and insects. This characteristic contributes to the sustainability of wood products because it provides for natural recycling of the constituent materials making up the wood. However, it may also be problematic because it could lead to deterioration of the wood product while still in service. Susceptibility of wood to decomposition depends on the properties of the wood (some species are more naturally resistant to decay than others) as well as the moisture content of the wood (most decay organisms require a moist environment to live and multiply).

Several options exist for reducing deterioration of wood products in service. First, good design practices that prevent or minimise standing water on wood surfaces will reduce the moisture content of the wood, hindering the growth of decay organisms. Second, choosing wood species that are more naturally decay resistant will reduce deterioration, though this option may be limited by the tree species available. Third, surface coatings may be applied to the wood to repel water and maintain a low moisture content. Finally, the wood may be treated with chemical wood preservatives that kill the decay organisms. Two main categories of chemical treatments exist: oil-borne preservatives such as creosote and pentachlorophenol, and water-borne preservatives such as copper-based solutions (Lebow, 2010). Regulations in many countries define the allowable uses of different types of preservatives, which differ between, for example, residential and industrial applications. The landscape of chemical wood preservatives has changed significantly in the last decades towards safer materials, and continues to change. The use of arsenic in wood preservative solutions, such as the once common chromated copper arsenate (CCA), has been phased out, particularly in residential applications. In the European Union, the Biocidal Products Directive (98/8/EC) covers many common wood preservatives including CCA, resulting in restrictions on their use. Recently, the Commission Directive 2011/71/EU included creosote in this category, leading to increasing restrictions on creosote use in Europe.

From an environmental perspective, there are advantages and disadvantages of using chemical wood preservatives. By prolonging the service life of wood products, chemical preservation reduces the level of forest harvest needed to sustain a given function from wood product use. However, this comes with the burden of an increased level of toxic materials in the built environment and in the manufacturing and waste management sectors. Furthermore, opportunities for recycling of preservative treated wood are more limited than for untreated wood (Felton and de Groot, 1996). Particular concerns include worker exposure to emissions from recycling processes, and interference by preservatives with the bonding of adhesives. Energy recovery from treated wood is also restricted, although treated wood can be incinerated under suitable combustion conditions with flue gas cleaning and appropriate ash disposal.

Research is underway to develop effective wood preservation methods that do not add to the toxicity burden in the environment. For example, the acetylation process chemically modifies wood and makes it more dimensionally stable and less susceptible to biological attack, particularly by decay fungi (Rowell, 2006). In this process, acetic anhydride reacts with the free hydroxyl groups on large molecules in the wood cell walls. The hydroxyl groups are replaced with acetyl groups, and acetic acid is formed as a by-product. Although the performance of acetylated wood is generally superior to untreated wood, the current cost of the process makes it uneconomical for most applications. Another example of wood preservation through chemical modification is furfurylation, in which wood is treated with furfuryl alcohol and then heated to cause polymerisation (Lande *et al.*, 2008). The result is a cross-linked furan polymer that is chemically bonded to the wood cell wall polymers. Furfuryl alcohol is a renewable material derived from furfural, produced from hydrolysed biomass waste. Furfurylated wood is currently produced commercially on a relatively small scale by several European firms.

Another effective wood preservative with decreased toxicity concerns is borate. Borates are low cost, odourless and colourless, have very low toxicity to mammals, and are broadly effective against decay fungi and insects. However, borate compounds do not become fixed in the wood and can readily be leached out by water. Use of borate-treated wood is thus typically restricted to internal structural members and other uses where the wood will not be exposed to water or ground contact. Researchers are investigating methods for maintaining borate compounds in the wood matrix to enable long lasting wood protection in wet environments. However, the preservative properties of borates are primarily due to the tetrahydroxyborate ion formed upon exposure to water, thus complete immobilisation of the borate compound is undesirable (Obanda *et al.*, 2008). Numerous strategies have been proposed to reduce borate leaching from wood to ensure long-lasting protection, including surface treatments to hinder water uptake, formation of organo-boron compounds that bind with wood molecules, inorganic combinations of boron and metals or silicon, and polymerisation of boron-containing compounds within the wood cells. An example of the last mentioned strategy is described by Thevenon *et al.* (2009), who treated wood with boric acid and wood tannin resins and found considerable resistance against leaching and fungal attack.

14.4 Building with wood materials

14.4.1 Materials, components and buildings

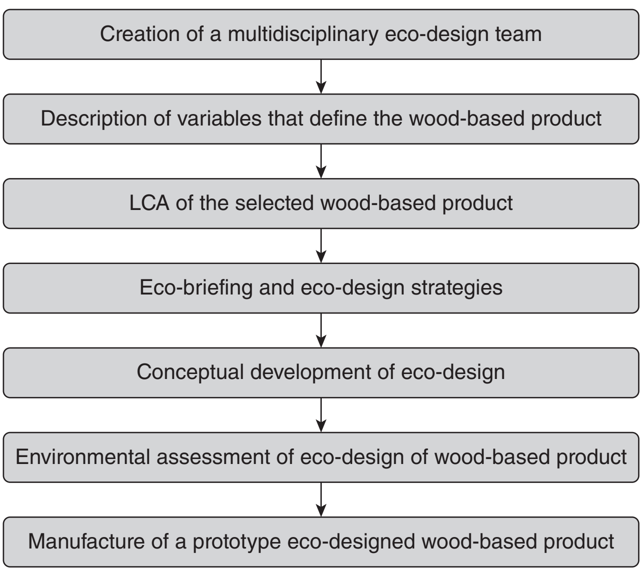
Various materials are combined to form building components such as walls, windows, floors, insulating materials, doors and furniture. In turn, these components are combined to form complete buildings. A commonly used unit by which environmental impacts are calculated is a unit mass of individual materials. For example, industrial process analyses commonly determine the primary energy required to manufacture a kilogram or tonne of material. This information can be useful input for a more elaborate analysis, but by itself is incomplete because the function of different materials cannot be directly compared. One tonne of lumber, for example, does not fulfil the same function as one tonne of steel. Similar analysis on the basis of unit volume of material suffers the same shortcoming. A more useful functional unit is to compare performance on the basis of the function provided by building components. That is, building components that provide the same function, but made of different material combinations, can be compared (Gustavsson and Sathre, 2011).

The environmental impacts of many such construction components have been quantified in recent years, generally showing that wood-based components have lower overall impacts than comparable products made of non-wood materials (Werner and Richter, 2007; Sathre and O'Connor, 2010a). For example, Richter *et al*. (1996), Kreissig *et al*. (1997), Asif *et al*. (2002), and Salazar and Sowlati (2008) all compared the environmental impacts of window frames made from different materials. LCA has also been used to compare the environmental performance of flooring materials (Jönsson *et al*., 1997; Jönsson, 1999; Nebel *et al*., 2006). González-García *et al*. (2012a) assessed the environmental profile of a ventilated wooden wall structure made of wood-based panels and other materials such as mineral wool and polyester resins. This study showed that the production of the wood-based panels was the main environmental hot spot due to the requirement of petroleum-based resins whose production results in toxic substance emissions as well as transport contributions. Environmental improvements were proposed by González-García *et al*. (2012a) based on the use of wood panels with lower environmental impact using wood from nearby forest plantations and renewable energy sources to fulfil the process energy requirements.

Buildings are complex systems, and a particular material may fulfil more than one function (e.g., structural support and thermal insulation), and a given building function may be fulfilled by a combination of materials. Changing one material may impact on other functions in various ways, for example sound transmission, fire protection, and the overall weight of the building and the required foundation design. Robust LCAs must ensure that these complex interactions between multiple system elements are accounted for within the functional unit. This is ideally done by comparing functionally equivalent versions of complete buildings made with different material mixes (Kotaji *et al*., 2003). This can be based on a generic hypothetical building (Björklund and Tillman, 1997), or a case study of completed buildings (Gustavsson *et al*., 2006b; Lippke *et al*., 2004; John *et al*., 2009). A general conclusion of such comparative studies is that wood-based construction systems tend to have lower environmental impacts than functionally equivalent systems using non-wood materials (Werner and Richter, 2007; Sathre and O'Connor, 2010a).

14.4.2 Eco-design in wood-based construction

The growing demand for knowledge about how products are made, where they are sourced from, what the environmental consequences of their production and use are, and how they are disposed of at the end of their service lives has provided an opportunity for the wood products sector to excel in the emerging market for green products (Bovea and Vidal, 2004). Embracing environmental strategies for optimising the life cycle of their product (including design, manufacture, use and end-of-life management), progressive manufacturers have adopted environmental accreditation with eco-labels such as Forest Stewardship Council (FSC) or Carbon Footprint (CF) as means to differentiate their products (Bovea and Vidal, 2004; Veisten, 2007). The application of sustainability criteria to the product design has received increasing attention in recent years. Eco-design, or Design for the Environment (DfE), is a concept that integrates multifaceted aspects of design and environmental considerations. The development of sustainable solutions for products or services is based on the minimisation of negative consequences under economic, environmental and social perspectives, throughout and beyond the life cycle of products (Charter and Tischner, 2001). Eco-design is a process that seeks to reduce the inherent environmental burdens associated with products. The stages of the eco-design methodology are shown in Fig. 14.3.



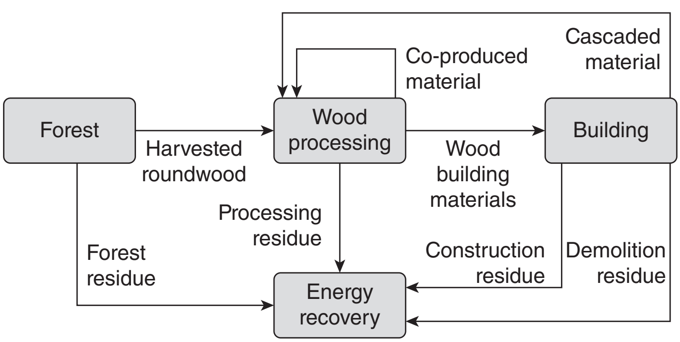
14.3 Stages in the methodology for the eco-design of a wood-based product.

An interdisciplinary design team is essential to the improvement of environmental aspects of product life cycle stages including material sourcing, processing, transport, packing, installation, use, maintenance, dismantling and end-of-life. Initial decisions made during the design phase have important consequences throughout the whole life cycle (Brezet and van Hemel, 1997). The eco-design process seeks to implement a vision for the reduction of overall environmental impacts, where the final disposition of the product is contemplated before it is even produced, with a plan for managing and minimising the waste generated throughout the whole life cycle (McDonough *et al*., 2003; Züst and Wimmer, 2004).

An increasing number of studies can be found in the literature that combine LCA and eco-design for wood-based products such as ventilated wooden walls (González-García *et al*., 2012a), wooden modular playgrounds (González-García *et al*., 2012b), furniture (González-García *et al*., 2012c), wooden containers for the food sector (González-García *et al*., 2011a), and kitchen cabinets and office tables (González-García *et al*., 2011c). In all of these studies, problematic environmental impacts were identified and improvement strategies were proposed in the eco-design of new products with a low environmental profile. Thus, the implementation of eco-design in the development of wood-based products helps to introduce alternatives within the production process, which allows identification of improvements and reduction of the environmental impacts with fewer iteration cycles.

14.5 Integrated energy and material flows

Integrating material and energy flows within and between the forestry, construction, energy, industry and waste management sectors (Fig. 14.4) can bring energetic, economic and environmental advantages (Sathre and Gustavsson, 2009). The energy sector is central, as it provides heat, fuels



14.4 Schematic diagram of potential biomass flows during the life cycle of wood building material.

and electricity for the other sectors and for society in general (Truong and Gustavsson, 2013). It can benefit by using by-products of the forestry and wood products sector as fuel, as well as other biomass materials that would otherwise be considered a waste product. The wood products industry has the potential to be largely self-sufficient in primary energy terms, but can benefit by providing biofuels and heat to other sectors, and receiving, for example, liquid biofuels to power forest and transport equipment. The waste management sector, which traditionally has received and disposed of materials such as construction site and demolition waste, can be a source of valuable biomass fuel to the energy sector. Thus, the closer integration of these different sectors can significantly reduce the overall life cycle impacts of a built environment based on forest resources.

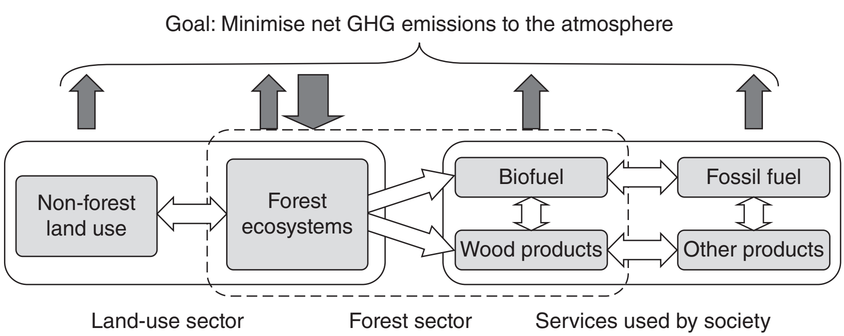
This integration of material and energy flows is already under way in many regions, and can be further optimised. The recovery and use of wood processing residues is now common in many areas, where previously such material was often disposed of as waste. The recovery of forest harvest residue for bioenergy is now done in some areas, although stumps and thinning residue are less commonly recovered (Eriksson *et al.*, 2007). Similarly, the recovery and use of wood-based construction and demolition residue takes place in some areas, but still goes unused in others. The final stage in the life cycle of a building is the demolition or disassembly of the building followed by the reuse, recycling or disposal of the materials. The percentage of demolition materials that is recoverable is variable, and depends on the practical limitations linked to the building design and whether material recovery is facilitated through deconstruction (Kibert, 2003). Systematic recovery of demolition wood is not yet practised in some areas, and demolition wood is instead landfilled. Consideration of the entire life cycle of a building material must include the fate of the material at the end of its service life.

Additional use of recovered wood material, such as reusing as lumber, reprocessing as particleboard, or pulping to form paper products, can improve the environmental performance of the material. Wood products are well suited for material cascading, which has been suggested as a strategy to increase the efficiency of resource use (Haberl and Geissler, 2000). Cascading is the sequential use of a resource for different purposes, as the resource quality degrades over time as it proceeds towards thermodynamic equilibrium. The cascade concept includes four dimensions of resource economy: resource quality, utilisation time, salvageability and consumption rate (Sirkin and ten Houten, 1994). In terms of these four characteristics, optimal utilisation of wood resources is achieved by: matching the resource quality to the task being performed, so as not to use a high-grade resource when a lower-grade one will suffice; increasing the total utility gained from a resource through prolonging the time during which it is used for various purposes; upgrading a resource through salvaging and reprocessing, where appropriate, for additional higher-grade uses; and balancing the usage rate of a resource with the capacity of forest land to regenerate lost resource quality.

A simple form of cascading is to burn a wood product at the end of its useful service life and recover the heat energy. Such a cascade chain has two links: material use and energy recovery. The efficient use of wood resources dictates that, at a minimum, the material is recovered and burned for energy recovery at the end of its useful life cycle. In some cases, particularly when forest resources are limited, it will be beneficial to employ a more complex cascade chain involving multiple material uses before final burning (Sathre and Gustavsson, 2006). In future, if more material and energy services are provided by biomass and fewer by fossil resources, wood cascading is likely to become more important by allowing more intensive use of limited biomass resources. The environmental performance of non-wood materials can also be affected by post-use management by, for example, recycling of metals and reuse of crushed concrete. Nevertheless, wood material has relatively more opportunity to improve its energetic and climatic performance through appropriate post-use management, due to its dual role of both material and fuel (Dodoo *et al.*, 2009).

14.6 Wood products and climate change

Managing forests so as to produce a yield of usable biomass, while simultaneously maintaining or increasing forest carbon stocks, is increasingly seen as a forest management strategy with large sustained mitigation benefits over the long term (IPCC, 2007) (see Fig. 14.5). The use of wood building materials instead of other materials contributes to climate change



14.5 Linkages between the forest sector and other sectors, with the overall goal of minimising net GHG emission to the atmosphere (adapted from IPCC, 2007).

mitigation through various mechanisms (Sathre and O'Connor, 2010a). A meta-analysis of 21 international studies of wood substitution found an average displacement factor of 2.1 tonnes of avoided carbon emissions per ton of carbon in wood products used in place of non-wood materials (Sathre and O'Connor, 2010b). The climate advantages of using wood products include: less fossil energy used to manufacture wood products compared with alternative materials; avoided industrial process carbon emissions such as in cement manufacturing; physical storage of carbon in forests and wood materials; use of wood by-products as biofuel to replace fossil fuels; and possible carbon sequestration in, and methane emissions from, wood products deposited in landfills. In this section we summarise the effects of each of these mechanisms.

14.6.1 Reduced fossil emissions from manufacturing

Manufacturing wood products typically requires less total energy, and in particular less fossil energy, than the manufacturing of most alternative materials. Cradle-to-gate analyses of material production, including the acquisition of raw materials (e.g., mining or forest management), transport, and processing into usable products, show that wood products need less production energy than a functionally equivalent amount of metals, concrete or bricks (Werner and Richter, 2007; Sathre and O'Connor, 2010a). Furthermore, much of the energy used in wood processing is thermal energy used for drying, for which wood processing residues are commonly used. Thus, the fossil carbon emission from wood product manufacturing is generally much lower than that of non-wood products. Composite wood products, while making more efficient use of roundwood raw materials, require a relatively higher use of fossil energy than do solid wood products. This energy, used for production of resins and additives as well as for the mechanical processing of wood fibres, is still commonly less than that needed for non-wood products. The development of green adhesives, described in Section 14.3.2, may reduce this fossil energy use.

14.6.2 Avoided industrial process emissions

Using wood products in place of cement-based products avoids the industrial process carbon emissions from cement manufacturing. CO_2 emissions are inherent to cement production, due to chemical reactions (calcination) during the transformation of raw materials into cement clinker. Avoided process emissions can be a significant part of the GHG benefits of wood products used in place of concrete and other cement-based materials (Gustavsson *et al.*, 2006b). While avoided calcination reaction emissions are well quantified, there is some uncertainty regarding the net life cycle effect of cement process emissions, due to CO_2 uptake by the carbonation reaction. Carbonation is a slow reaction that occurs over the life cycle of cement products, and involves reabsorption of part of the CO_2 that was initially emitted (Dodoo *et al.*, 2009). Nevertheless, as carbonation uptake is less than calcination emission, process emissions are avoided when substituting wood in place of cement products.

14.6.3 Carbon storage in wood products

Wood material is composed of about 50% carbon by dry weight, this carbon coming from the CO_2 removed from the atmosphere by the growing tree. In other words, wood products provide a physical storage of carbon that was previously in the atmosphere as a GHG (Lippke *et al.*, 2010). The climatic significance of carbon storage in wood products depends on the dynamics of the products pool as a whole, i.e., whether the total quantity of stored carbon is increasing, decreasing or stable. Atmospheric carbon concentration is affected by changes in the size of the wood product pool, rather than by the size of the pool itself (Gustavsson and Sathre, 2011). In the short to medium term, climate benefits can result from increasing the total carbon stock in wood products, by using more wood products or using longer-lived wood products. In the long term, as the stock of products stabilises at a higher level, wood products provide a stable pool of carbon as new wood entering the pool is balanced by old wood leaving the pool. Consideration of the long-term carbon dynamics of wood products shows that the substitution effect of avoiding fossil emissions is ultimately more significant than the carbon stored in wood products (Eriksson *et al.*, 2007; Poudel *et al.*, 2012).

14.6.4 Carbon storage in forest ecosystems

Over a complete rotation period of sustainable yield forestry, the carbon content in tree biomass remains unchanged, by definition (Lippke *et al.*, 2011). Forest soils often store more carbon than forest biomass, and soil carbon stock in managed forests generally maintains a dynamic equilibrium level over multiple rotations. Wood production in managed forests must be distinguished from the carbon balance effects of harvesting primary forests; conversion of primary (old-growth) forests to secondary, managed forests results in a loss of stored carbon from both biomass and soils, before the forest carbon stocks again reach dynamic equilibrium. The level of the new equilibrium depends on soil characteristics, forest management intensity and other factors. Afforestation, or the creation of forests on previously non-forested land, generally increases the carbon stock in biomass and soil as well as producing wood for product substitution.

14.6.5 Biofuel substitution and avoided fossil emissions

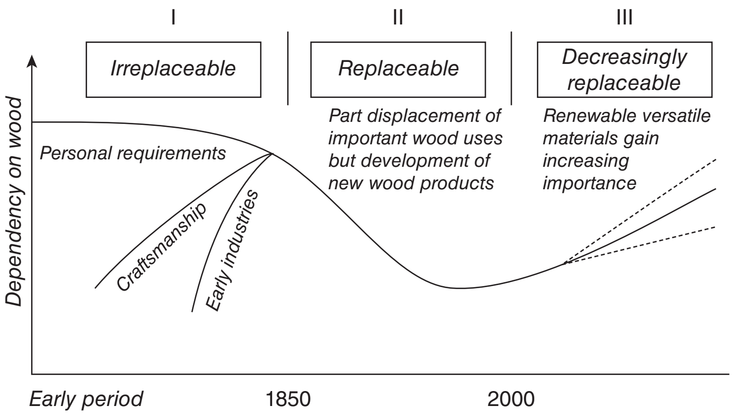
The wood contained in a finished forest product is only a part of the total biomass flow associated with the product. Substantial biomass residues are generated during forest thinning and harvest operations, during primary and secondary wood processing, and at the end of the service life of a wood product. These by-products can be used as biofuel to replace fossil fuels, thus avoiding fossil carbon emissions. The quantification of GHG benefits due to the use of residues from the wood product value chain is not straightforward; issues include the allocation of benefits to the different biomass fractions, varying carbon intensity of the fossil fuel replaced, leakage (i.e., a unit of additional biofuel does not necessarily lead to a unit reduction of fossil fuel use), potential soil carbon stock change due to removal of harvesting residues, and uncertainties about how post-use wood products will be handled by future waste management systems (Gustavsson and Sathre, 2011). Nevertheless, the recovery and combustion of the biomass by-products associated with wood products appears to be the single most significant contributor to the life cycle GHG benefits of wood product use (Sathre and O'Connor, 2010b).

14.6.6 Carbon dynamics of landfilled wood

Some wood products are currently deposited in landfills at the end of their service life. Carbon dynamics in landfills are recognised to be quite variable, and can have a significant impact on the life cycle GHG balance of the wood product (Micales and Skog, 1997). A fraction of the carbon content in landfilled wood will likely remain in (semi)permanent storage, providing climate benefits. Another fraction may decompose into methane, which has much higher global warming potential (GWP) than CO_2. However, methane gas from landfills can be partially recovered and used as a biofuel to replace fossil fuels. Thus, the landfilling option for post-use wood products carries great uncertainties, and could result in climate benefits (partial sequestration in landfills, and partial production of methane biofuel) or climate impact (emission of methane to the atmosphere). Landfilling of wood forgoes the assured opportunity of complete energy recovery from post-use wood products, and is not recommended from a resource efficiency perspective.

14.7 Wood building materials: past and future

Wood has long been a primary source of material and energy for human society (Perlin, 1989). Until recent centuries, wood was irreplaceable as the most important raw material for construction, agriculture, crafts,



14.6 Relative importance of wood material in past, present, and future (source: Sathre and Gustavsson, 2009; from Schulz, 1993).

shipbuilding, etc. More recently, however, many previous uses of wood have been replaced by materials such as concrete, metals and plastics, and by non-renewable fossil fuels such as coal, oil and natural gas. Schulz (1993) suggested that this substitution of wood by other materials and energy sources may be reversed and a new phase of increased wood use may begin due to environmental concerns and eventual supply constraints of non-renewable raw materials and fuels (Fig. 14.6).

The level of current wood use in building construction varies significantly between countries. The use of wood for constructing single-family houses is rather low in Europe, except in the Nordic countries (Gustavsson *et al*., 2006a). Wood is commonly used in Nordic countries for single-family houses, but is less common in multi-storey apartment buildings. In contrast, wood is commonly used in North America for construction of both single-family and multi-family houses. Wood use practices in some parts of Europe are still affected by historical path dependencies. In response to large city fires during the late 19th century, several European countries introduced regulations prohibiting the use of wood frames in multi-storey buildings.

This was reversed in 1989 by a directive from the European Commission (Council Directive 89/106/EEC), which was later replaced by Regulation (EU) No. 305/2011. These regulations effectively state that any material that fulfils the functional requirements can be used for construction of multi-storey buildings. However, over two decades after the change in policy, the use of wood frames in the construction of multi-storey buildings in Europe is still low. The slow re-emergence of wood construction in Europe is largely due to the path dependency of the established non-wood construction system (Mahapatra and Gustavsson, 2008). This system consists of an inter-linked set of technologies, actors and institutions following a specific path implicitly supported by institutional, economic and social factors.

Several measures could help to overcome these hindrances and promote wood construction, including investments in knowledge creation, incentives for entry of new firms, and the promotion of collaboration between different sectors (e.g., construction and forestry) (Mahapatra *et al.*, 2012). Economic instruments to internalise the external costs of producing building materials, e.g. the social costs of GHG emissions, would improve the economic competitiveness of wood building material (Sathre and Gustavsson, 2007). The development of effective and environmentally compatible wood adhesives and preservatives would expand the life cycle opportunities for reuse and recycling of forest biomass. Increased use of wood-based building materials would be fully compatible with a broader integration of sustainable biomass resources into the material economy, as only about 20–25% of the potential harvest of forest biomass is actually built into the construction. The remaining biomass (e.g., forest, processing and construction residues) could be used for other purposes, providing economic and environmental synergies between sectors. Biorefineries may be developed to differentially extract and process the components of woody biomass such as cellulose, hemicellulose, lignin, and extractives to co-produce a range of products (Amidon *et al.*, 2008). High system-wide efficiencies can be gained through co-production at varying scales of woody biomass feedstock into, for example, district heat, electricity, and liquid and solid biofuels (Truong and Gustavsson, 2013). Such integrated biomass-based material and energy systems may contribute to fulfilling multiple societal needs, by efficiently using natural resources in a sustainable manner.

The use of wood-based building materials can contribute to a sustainable built environment based on resource-efficient systems with low environmental impact. Life cycle and system perspectives of the built environment are needed, so that all the life cycle phases – production, operation, maintenance and end-of-life – are considered and optimised as a whole, including the energy and material chains from natural resources to final services. Wood building products from sustainably managed forests are a renewable resource that can provide multiple benefits during their life cycle. In addition to their structural and architectural use within a building, the life cycle wood product chain produces significant quantities of biomass co-products that can be used as a sustainable bioenergy source to replace fossil fuels. The use of forest resources in the built environment can play an important role in a long-term strategy for sustainable development and climate change mitigation.

14.8 Sources of further information

14.8.1 Institutions and agencies

- US Forest Product Laboratory, United States. http://www.fpl.fs.fed.us/
- FPInnovations Wood Products Research Institute, Canada. http://www.fpinnovations.ca/
- SP Trä (SP Wood Technology), Sweden. http://www.sp.se/en/units/wood/
- Treteknisk (Norwegian Institute of Wood Technology), Norway. http://www.treteknisk.com/
- European Forest Institute. http://www.efi.int/
- FAO Forestry, Food and Agricultural Organisation of the United Nations. http://www.fao.org/forestry/en/
- Skogforsk (Forestry Research Institute of Sweden). http://www.skogforsk.se

14.8.2 Scientific journals

Forest Products Journal. http://www.forestprod.org/buy_publications/forest_products_journal.php

European Journal of Forest Research. http://link.springer.com/journal/10342

European Journal of Wood and Wood Products. http://link.springer.com/journal/107

Scandinavian Journal of Forest Research. http://www.tandfonline.com/loi/sfor20

Canadian Journal of Forest Research. http://www.nrcresearchpress.com/journal/cjfr

Forest Ecology and Management. http://www.journals.elsevier.com/forest-ecology-and-management/

International Journal of Life Cycle Assessment. http://link.springer.com/journal/11367

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