# Environmental assessment of bio-based building materials

9

*E. Suttie**, *C. Hill*†,‡, *G. Sandin*§, *A. Kutnar*¶,‖, *C. Ganne-Chédeville*#, *F. Lowres**, *A.C. Dias***

*BRE, Watford, United Kingdom, †JCH Industrial Ecology Ltd, Bangor, United Kingdom, ‡NIBIO, Ås, Norway, §RISE Research Institutes of Sweden, Gothenburg, Sweden, ¶University of Primorska, Koper, Slovenia, ‖InnoRenew CoE, Izola, Slovenia, #Bern University of Applied Sciences, Biel/Bienne, Switzerland, **University of Aveiro, Aveiro, Portugal

## 9.1 Introduction

The imperative for the construction industry is to drive down the contribution the sector makes to global $CO_2$ emissions by delivering energy-efficient buildings more efficiently using the lowest impact construction products. Approximately 50% of global $CO_2$ emissions are associated with the built environment with half coming from the operational impact of buildings such as heating, lighting and cooling and half again embodied through manufacture and processing in the materials and products that are chosen for the construction.

As the deeper- and far-reaching impacts of climate change and global warming became apparent in the 1990s, regulators were motivated in some countries to act and tackle their commitments to the Kyoto Protocol as their targets to reduce carbon emissions became ratified by national governments. Much of the regulation was directed towards the construction industry to build upon platforms already in existence to promote delivery of energy-efficient buildings. In addition, consideration was being given to the material and products that were being selected to create the energy-efficient homes and commercial properties of the future and for the refurbishment of existing building stocks. From the mid-1990s, it was clear that designers and architects had a crucial role in the creation of low-carbon buildings so tools and methods were targeted at them including robust information to enable meaningful sustainability choices to be made at the design stage. Coming to the present day, in 2016, we have a harmonised life cycle assessment (*LCA*) methodology in Europe and a uniform process of delivery of environmental product declarations (*EPDs*) to showcase the sustainability attributes of construction products across Europe.

Considerable discussion around the embodied impacts of construction products and materials focuses on the carbon footprint of the product and its contribution to greenhouse gas (*GHG*) emissions. From the perspective of bio-based construction products and materials, this seems to present an opportunity as the starting point for a bio-based material is the carbon sequestered from the atmosphere to create the material—resulting in a negative-carbon starting point. As this chapter explores, it is not quite that simple as consideration of the whole life cycle impacts needs to be taken into account,

**Performance of Bio-based Building Materials. http://dx.doi.org/10.1016/B978-0-08-100982-6.00009-4**

a critical phase being the in-service phase—a products fitness for purpose—where premature failure of a material or product will lead to significant additional environmental burdens and a poor LCA outcome.

This chapter considers the environmental assessment of building materials and some examples and features of bio-based materials. The modules of LCA are detailed, and carbon accounting is considered including the unique characteristic of bio-based materials—the carbon sequestered in them. The contributions to the circular economy, bio-economy and low-carbon economy are discussed. There are firmly established and well-recognised methods for measuring environment profiles and labelling products. The labelled products are then considered in the context of how the environmental assessment of buildings is conducted and communicated.

## 9.2 Environmental assessment of bio-based building materials

### 9.2.1 Environmental assessment of building materials from processing, use and end of life phase

Several environmental impacts arise along the life cycle of building materials, that is, from raw material supply up to end of life and including manufacturing, construction process and use stages. Although different tools may be used to evaluate those impacts, LCA, which consists of the compilation and evaluation of the inputs, outputs and corresponding environmental impacts of a product throughout its life cycle (ISO 14044, ISO, 2006c), has advantages compared with other tools. LCA addresses both the entire life cycle of a product and a comprehensive range of environmental impacts, resulting in the avoidance of problem shifting, for example, from one life cycle stage to another or from one environmental compartment to another. LCA has been applied to different types of bio-based building materials, such as modified wood (Ferreira *et al.*, 2016; Hill and Norton, 2014), wood-based panels (Rivela *et al.*, 2005; Werner and Richter, 2007; Wilson, 2009; dos Santos *et al.*, 2014; Silva *et al.*, 2013, 2014), corkboards (Sierra-Pérez *et al.*, 2016) and materials based on agricultural (Ardente *et al.*, 2008; Silva *et al.*, 2014) and animal resources (Murphy and Norton, 2008). Nowadays, there are also several EPDs focusing on bio-based building materials. In Europe, most of them follow the EN 15804 (CEN (2012b)) standard that provides core product category rules (*PCR*) for all construction products and services to ensure that the EPDs are elaborated, verified and presented in a harmonised way. This standard is organised in modules (from A to D) and distinguishes four stages within the life cycle of a building product: product stage, construction process stage, use stage and end-of-life stage. The main environmental impacts associated with each stage are presented below for bio-based building materials.

#### 9.2.1.1 Product stage (modules A1 to A3)

These modules give information about raw material supply, transportation and manufacturing. It corresponds to the so-called ‘cradle-to-gate’ assessment, which consider all flows and activities from the production, harvesting or collection of the raw material to the finished and packed product ready to be transported to the construction site. If recycled products are used as raw material, all processes linked to their manufacturing are also accounted in these modules.

### A1: Raw material supply

Bio-based building materials can be made from several resources. Wood is one of the main bio-based materials used in the world, but several other bioresources are also used in construction, for example, bamboo, corn residues or sheep wool. We can separate them in two main categories: forest products and agriculture/animal products. Additionally, additives (mainly glues, coatings and preservation substances) from a bio-based or from fossil sources can be used for producing building materials (e.g. glues for particle boards, matrices for wood-plastic composites or preservatives for impregnated wood). Finally, recycled bio-based material can be used as raw material for bio-based building (e.g. recycled paper or solid wood).

*Forest products.* For the production of raw materials derived from forests, such as wood, cork or bamboo, a number of operations are carried out during forest management activities that originate environmental impacts (van Dam and Bos, 2004; van der Lugt *et al.*, 2006; Dias and Arroja, 2012; González-García *et al.*, 2013). The burning of fossil fuels in mechanised operations (e.g. cleaning, thinning, pruning or harvesting) generates air emissions such as carbon dioxide ($CO_2$), sulphur dioxide ($SO_2$) and nitrogen oxides ($NO_x$), which contribute, for example, to climate change, acidification and formation of photochemical oxidants. Fertiliser application may cause eutrophication due to nutrient release to the environment and can contribute to climate change as a result of nitrous oxide ($N_2O$) emission to the atmosphere. The application of pesticides may lead to toxicity-related impacts. Other impacts associated with land use may also arise such as changes in soil organic carbon and fertility, biodiversity, erosion and water use. On the other hand, forest ecosystems have the capacity to uptake $CO_2$ from the atmosphere and store this carbon in living (stemwood, branches, foliage and roots) and dead biomass (litter, wood debris and soil organic matter), which is an environmental benefit.

*Agriculture and animal products:* Global land use is characterised by competition between food, fuel and feed production. There are higher risks for indirect land-use change (*ILUC*) and the associated environmental impacts for agricultural production. For example, biofuel production typically takes place on cropland, which was previously used for food production. Since this agricultural production is still necessary, it may be partly displaced to previously noncropland such as grasslands and forests. This process is known as indirect land-use change (ILUC). ILUC risks negating the GHG savings that result from increased biofuels because grasslands and forests typically absorb high levels of $CO_2$ (European Commission, 2012).

Many products from agriculture and livestock husbandry can be used as raw material in buildings. Amongst them are straw, flax, sugar cane bagasse, corn, hemp, rice husk, groundnut shells, kenaf, reed, sheep wool, casein and polylactic acid (*PLA*) (Schmidt *et al.*, 2004; Ardente *et al.*, 2008; Murphy and Norton, 2008; Menet and Gruescu, 2012; Silva *et al.*, 2014; Chaussinand *et al.*, 2015; Palumbo, 2015).

Conventional agricultural processes need fuel, fertiliser and pesticides similar to a forestry processes. Besides this, land use and soil preparation can be intensive and can lead to degradation of the soil leading to natural resources loss. Agricultural processes are responsible for emissions and environmental impacts in the same way as forest products. But for the cultivation of crops, fertilisers, pesticides, fuels and machine, utilisation is higher due to the annual cycles of cultivation. dos Santos *et al.* (2014) showed that the production of bagasse was the most relevant flow for eutrophication in an LCA of particle board due to the utilisation of fertilisers. The same observations were made by Ganne-Chédeville and Diederichs (2015) for the production of PLA contained in ultralight particle boards. Some crops need a high amount of water for irrigation. Intensive use of water for growing crops can lead to reduction of fresh water availability, which accounts as natural resource depletion. To a greater extent, it can also lead to ecotoxicological effects, by concentration of pollutants and biodiversity loss. Some bioresources can be directly collected from nature, for example, reed grass growing naturally in wetlands for roofing thatch. This avoids environmental impacts due to fertilisation and use of pesticides. The environmental impacts of animal hairs, mainly sheep wool, have been extensively assed (Henry, 2012). The major impacts of wool production are methane ($CH_4$) emissions from sheep farms, which contribute to climate change and water consumption of the wool treatment processes. Other impacts are due to growing of biomass for feeding the sheep (impacts of agricultural products) and the energy and fuels used in the farms and for the wool treatments (mainly $CO_2$, $SO_2$ and $NO_x$ emitted). Agriculture and animal production systems have a lot of co-products that are the basis for bio-based building materials. For example, meat and wool are two coproducts of the sheep production system. Environmental burdens of the coproduct are attributed mostly through economical allocation but sometimes also through mass allocation (Biswas *et al.*, 2010; Jones *et al.*, 2014).

*Additives.* Depending on their composition, manufacturing process and if they are produced out of fossil or bio-based sources, additives can have relevant environmental impacts even if they are used in small quantities. Preservatives are additives often used to extend the service life of bio-based building materials. Oil-borne preservatives such as creosote or water-borne preservatives such as copper or boron-based solutions are common for wood preservation (Hill, 2006). Processes of distillation and pyrolysis go through the combustion of fossil fuels or biomass, contributing to climate change, acidification, photo oxidation and resources depletion. In the case of metal-based preservatives (e.g. copper), raw material collection needs mining activities (loading, hauling, crushing and grinding), which are responsible for abiotic resource depletion, land use as well as air pollution (emissions of particles) and global warming potential due to fuel usage (Norgate and Haque, 2010). The production of petrochemical, mainly synthetic binders and plastics (e.g. urea-formaldehyde, polyurethane, melamine, polyethylene, polyester or phenolic resins), is responsible for fossil resource depletion and often needs high amounts of input energy as fossil fuels, which lead to $CO_2$ emissions and contribute strongly to climate change (Rivela *et al.*, 2005; Werner and Richter, 2007; González-García *et al.*, 2009; Wilson, 2009; Silva *et al.*, 2014; Sathre and González-García, 2014; Ganne-Chédeville and Diederichs, 2015). On the other side, bio-based additives, for example, tannin (Pizzi, 2008), corn starch, rubber, PLA

(Ganne-Chédeville and Diederichs, 2015), sodium alginate (Palumbo, 2015), proteins, linseed oil or other natural extracts from plants and trees, can be used. Even if they are based on renewable resources, they also need to be grown, harvested (see environmental burdens of forest and agricultural products), processed, extracted or treated, which lead mostly to environmental burdens linked to emissions of energy production and consumption.

*Recycled products:* Recycled products are interesting alternatives for reducing the environmental impact of raw materials. Only the environmental burden linked to the manufacturing of these products that are not included in the module C3 (waste treatment/preparation for recycling) is to be accounted in an LCA of the products (EN 15804, CEN, 2012b). If the product can directly be reused without transformation (e.g. reuse of a wood beam), no environmental impact should be attributed to the raw material phase. But some products need to be transformed in order to be reused. For example, recycled paper process includes water and chemical consumption, heat and mechanical treatment operations (Arena *et al.*, 2004). This process is responsible for environmental impacts like fresh water depletion, water ecotoxicity, climate change, acidification and photo oxidation.

### A2: Transportation from cultivation or production place to product manufacturing place

The magnitude of the environmental impacts derived from raw material transport depends both on the distances travelled and the transport mean (truck, train, ship or airplane). Besides, within each transport mean, variations may occur depending on the optimisation level of the transport and the density of the material transported, which affect the load capacity and also on the fuel type and vehicle technology. In the case of an electric train, it also depends on the electricity production mix in the region. The impacts originate mostly from air emissions (e.g. $CO_2$, $NO_x$ and particles) not only from fuel combustion but also from the production of capital goods such as road infrastructure and vehicles (Frischknecht *et al.*, 2007).

### A3: Manufacturing of product

Manufacturing of the bio-based building materials comprises many steps and may be very different from one product to another. The environmental impacts of three main groups of activities in manufacturing are presented here: common operation, modification treatments and production of bio-based boards.

*Common manufacturing steps:* Drying, sawing, planning, sanding, gluing and packaging are typical manufacturing processes of bio-based building materials. Drying is one of the critical processes as hot air must be produced through the combustion of fossil fuels and consequently leads mainly to $CO_2$, $SO_2$ and $NO_x$ emissions responsible for climate change, acidification and photo oxidation as well as abiotic resource depletion. On the other hand, companies that are producing bio-based materials often use production waste (e.g. sawdust and wood shavings) as fuel for drying. In this closed-loop situation, $CO_2$ emissions are accounted as biogenic and therefore assumed to be climate neutral in global warming potential calculations. Sawing, planning and gluing activities need mainly electricity, so that their environmental impact is strongly linked to the electricity mix used in the region. Renewable energy sources (photovoltaic, wind, hydraulic and biomass) can replace fossil fuels (coal, gas and oil) and nuclear sources to reduce the environmental impacts. Although environmental impacts of the infrastructure (capital goods) accounted to the products are commonly neglected, they can substantially contribute to ecotoxicity, fossil resource depletion and climate change (Frischknecht *et al.*, 2007).

*Modifying forest products:* Bio-based raw material modification for the production of bio-based building materials includes mainly application or impregnation processes and thermal treatment infrastructure (Hill, 2006; Ferreira *et al.*, 2016). Treatment infrastructures comprise typically of a cylindrical pressure vessel (autoclave) often equipped with vacuum pumps and/or an electrically operated heating system. Here also, impacts are depending on the electricity mix used. Substances used in impregnation/modification processes need to be first diluted in water, causing water-resource depletion. Sometimes, leakages can happen during processing, which often lead to water ecotoxicity, depending on the toxicological properties of the substance used and the site environmental management plan. During the modification processes and at the end of the processes, impregnation substances and/or extracted substances due to vacuum and heat treatment are released into process liquids. Those can be problematic wastes and need to be treated. For impregnation processes, it is mostly possible to reuse the preservatives or chemical again for a next impregnation cycle. For thermal treatment, the residue present in the process water should be concentrated and the waste water treated, which requires electricity. Finally, the residues must be recycled. If this is not possible, they are landfilled, which lead to land use and, depending on their composition, ecotoxicological impacts in soil and water compartments.

*Producing bio-based boards:* Environmental impacts associated with the production of bio-based boards (particle board, medium density fiberboard (*MDF*), oriented strand board (*OSB*), light density fiberboard (*LDF*) and plywood) and insulation boards arise during the combustion of fuel for hot pressing and as the consumption of electricity as veneers, particles or fibres is prepared and the boards are finished (sanding) (Rivela *et al.*, 2005; Werner and Richter, 2007; González-García *et al.*, 2009; Wilson, 2009; Silva *et al.*, 2014; Sathre and González-García, 2014; Ganne-Chédeville and Diederichs, 2015). Corkboards are either cork agglomerates made up with cork granules bound by adhesives such as polyurethane, melamine or rubber (called composition or white cork agglomerates) or cork agglomerates exclusively made of cork where the cork granules are thermally self-bonded (called pure expanded or black cork agglomerates). The environmental impacts of manufacturing are usually higher in the production of the first type of corkboards, mainly due to fossil fuels used for thermal energy production, which are not required in the case of expanded cork agglomerates (Pargana *et al.*, 2014; Sierra-Pérez *et al.*, 2016). Some insulation boards include, in addition to the common steps of board manufacturing, a foam-expansion step using blowing agents (e.g. chlorofluorocarbons, pentane or liquid $CO_2$), which are released into the environment (Ganne-Chédeville and Diederichs, 2015). Depending on their properties, they can have more or less contribution to climate change, ozone depletion or human toxicity. Bio-based board containing formaldehyde or isocyanates can, through the release of these compounds during the manufacturing, lead to human toxicity impacts (He *et al.*, 2012). Finally, some bio-based boards have an extrusion step (e.g. wood-plastic composites), which is energy-intensive for which environmental impacts are directly linked to the electricity mix in the region.

#### *9.2.1.2 Construction stage (modules A4 to A5)*

These modules give information about product transportation and installation processes as part of the building. They also include processing and disposal of generated wastes (e.g. 'cut to fit on site' waste and packaging waste) during the installation process. The impacts from the product transportation are similar to those associated with raw material transportation, as referred above. Not only the impacts from the installation processes may include some on-site impacts mostly related to air emissions but also the impacts from the production of energy and ancillary materials used. The impacts from waste management greatly depend on the type of materials and processes involved. Kellenberger and Althaus (2009) found that, in general, the impacts from transport and production of ancillary materials (joints, connectors, etc.) may be significant, whilst the impacts from the building process and cutting waste were less significant.

#### *9.2.1.3 Use stage (modules B1 to B7)*

These modules give information about the environmental impacts due to the use, maintenance, repair, replacement and renovation of the building fabric, as well as to the operation of the building, mainly related with energy and water flows. When bio-based materials treated with preservatives are used outdoors, leaching processes may take place with the release of chemicals to terrestrial and aquatic environments, causing toxicity-related impacts (Hingston *et al.*, 2001). Also, formaldehyde and other volatile organic compounds (*VOCs*) may be emitted during the use of bio-based materials incorporating adhesives or coatings, both outdoors and indoors (Roffael, 2006). These emissions are particularly impactful indoors, where they are recognised as causing multiple effects on human health, comfort and productivity. The impacts from maintenance, repair, replacement and renovation result mainly from the consumption of energy, water, components (e.g. door and window) and ancillary materials (e.g. paints and varnishes), as well as from the management of produced wastes and transport of components, materials and wastes. The magnitude of these impacts depends on physical building characteristics such as applied building services and material lifespan, as well as other factors such as the rate of deterioration and maintenance activities (Blom *et al.*, 2010). The operational impacts of the building usually dominate the cradle-to-grave impacts mainly due to the high-energy consumption to satisfy heating, air conditioning, electricity requirements and hot water production (Bribián *et al.*, 2009; Gustavsson *et al.*, 2010). Though it is worth noting that as buildings become more energy efficient, the embodied energy of the products used to build or refurbish the building becomes proportionally more significant as the lifetime operational energy reduces. However, in some cases, buildings incorporating higher proportions of bio-based products normally have lower environmental impacts during the use stage as they require less energy (Bribián *et al.*, 2011; Pajchrowski *et al.*, 2014).

#### 9.2.1.4 End of life stage (C1 to C4)

These modules contain all processes for the deconstruction, transport to waste treatment, preparation for recycling and/or final disposal. For deconstruction, mainly fossil-fuel-powered machines are used. The environmental impacts of the transport to the waste treatment place depend on the level of optimisation of the transportation system, the distance to the elimination place, the type of transportation and the density of the material. Lighter materials will cause less fuel consumption during transport (Murphy and Norton, 2008; Ganne-Chédeville and Diederichs, 2015). Preparation for recycling can contain diverse processes like crushing, selecting or digesting, which needs electricity and can release GHGs. In most cases, bio-based materials are disposed of through incineration for energy recovery where they release combustion gases, resulting in impacts like acidification, eutrophication, climate change and photo oxidation. Products containing fossil-based additives (e.g. urea-formaldehyde glue) will release fossil $CO_2$, contributing to climate change. Depending on the type of incineration system, other gases and particles can be released, causing ecotoxicity and human toxicity. Municipal incineration of bio-based building material often leads to low environmental performance due to the specific burdens of the incineration systems and because the materials are mixed with nonbio-based materials. Wastes from incineration need to be landfilled, which cause impacts in the categories of land use, soil ecotoxicity and climate change. Benefits of energy recovery from bio-based material incineration, avoiding the utilisation of fossil fuel for heat and electricity generation, are declared in the informative module D (benefits and loads beyond the product system boundary). If system expansion is applied (module D considered in the system limits), this leads often to a drastic reduction of the global warming potential of the product. Finally, the product can be directly landfilled, which has as a main consequence an impact in land use and, depending on its composition, ecotoxicity in soil and water as well as climate change due to methane and $CO_2$ released during decay processes. However, the anaerobic decay of some materials like wood, cork or paper is incomplete leading to long-term carbon storage in landfills (De la Cruz *et al.*, 2013).

### 9.2.2 Carbon accounting

Anthropogenic GHG emissions are making a substantial contribution to climate change (Intergovernmental Panel on Climate Change (*IPCC*), 2013). Since preindustrial times (before 1750), the concentration of carbon dioxide in the atmosphere has risen from a baseline level of 280 ppm (parts per million) to over 400 ppm at present. When the global warming effects of the other GHGs (primarily methane and nitrous oxide) are also taken into account, the level is around 450 ppm of carbon dioxide equivalents ($CO_2e$). Levels of GHGs are presently higher than they have been for any time in the past 800,000 years. These contributions to the increase in atmospheric $CO_2$ concentration since the industrial revolution come mainly from the combustion of fossil fuels, gas flaring and emissions associated with cement production. Other sources include deforestation, land-use change and biomass burning (contributing about 20%) (IPCC, 2007). Although the atmospheric GHG levels continue to increase, there are various natural processes by which atmospheric carbon dioxide is removed from the atmosphere. These are the following:

- photosynthetic production of biomass (terrestrial and aquatic)
- weathering of silicate rocks
- dissolution in the oceans

If all human additions of carbon dioxide to the atmosphere were to cease immediately, the atmospheric concentration would gradually return towards preindustrial levels. About 50% of the increase above the background level of 280 ppm would be removed in 30 years. This is assuming that anthropogenic interference in the climate does not lead to irreversible effects, such as melting of methane clathrates or oxidation of peat. The IPCC (2013) agrees that 'most aspects of climate change will persist for many centuries even if emissions of $CO_2$ are stopped' and that in human timescales a large fraction of anthropogenic climate change resulting from $CO_2$ emissions is irreversible with 15%–40% of emitted $CO_2$ remaining in the atmosphere for over 1000 years.

The management of carbon in the biosphere differs from fossil carbon management in that carbon can both be emitted from and sequestered to the biosphere. Whether there is a net radiative forcing, cooling or equilibrium depends on the balance and timing of the release and sequestration of the biogenic carbon. The amount of carbon stored in the living biomass of the planet totals up to 600–1000 Gt of carbon, with something of the order of 1200 Gt being locked up in dead biomass. Most of the carbon of the terrestrial biosphere is stored in forests, which contain about 86% of the above-ground biogenic carbon and 73% of the carbon stored in the soil. Due to the activities of humanity, these carbon pools are reducing in size; carbon stocks in global forests are decreasing by 1.1 Gt/year. However, in most of the countries of Europe, the forest utilisation rate (fellings as a percentage of the annual increment) is <100%, meaning that the carbon pool in European forests is increasing in size. With the current rate of timber harvesting in Europe, forests will move into older age classes, and the net increment of wood material will consequently decline (Nabuurs *et al.*, 2002). This provides an opportunity for increasing fellings to improve the carbon sequestration potential of forests. Furthermore, the utilisation of harvested wood products (*HWPs*) in long-life products also allows for the carbon storage benefits of timber to be extended beyond the forest. The use of biomass in the built environment represents a stable and easily accountable way of storing atmospheric carbon for long periods of time, creating a new carbon pool. Furthermore, the substitution of other building materials that often have a higher carbon footprint brings additional benefits. The question is how can this carbon storage benefit be measured and reported?

Carbon accounting refers to processes used to measure and track the flows of carbon atoms through technological systems and how these interact with the environment. Methodologies for carbon accounting are assuming greater importance due to concerns regarding the impact of the release of fossil carbon into the atmosphere, primarily as carbon dioxide and methane. It is an essential element of carbon-trading schemes, such as the European Union Emissions Trading System, and it is also needed in order to report on national GHG inventories required under the Kyoto

Protocol. Carbon accounting can also be used as a means of supporting informed decisions about products and processes, using LCA methodologies; these are sometimes referred to as carbon footprints. Carbon-trading schemes have been introduced to internalise the external costs of carbon emissions and are a means by which countries are able to meet their obligations under the Kyoto Protocol. The EU launched a carbon-trading scheme in 2005, covering power plants, aviation and energy-intensive industries. There are various carbon-trading schemes around the world, but there is no global trading scheme at present. In a future carbon-trading market, it is envisaged that carbon credits could be given for the storage of atmospheric carbon (as biogenic products) in buildings. The value placed upon the storage of atmospheric carbon should be represented in the market. For example, credits could be given for the use of timber in construction, an idea that requires deep scrutiny in the context of existing methodologies for assessing the sustainability of construction products and buildings. The storage of atmospheric carbon is an important component of a bio-based construction product life cycle, but equally, other questions need addressing: How long the carbon will be stored? What happens to the carbon at the products end of life?

The role of HWPs in mitigating GHG emissions has only recently been recognised by the Kyoto Protocol. For the first commitment period (2008–12), it was assumed that the quantity of carbon leaving the HWP pool every year was equal to the annual inflow. For the second commitment period (2013–20), the carbon accounting can now include carbon stock changes in the HWP pool. Although the IPCC recognises the importance of the built environment, its mitigation strategies listed 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 there is no consideration given to the potential for timber and other plant-derived products to act as carbon stores in the built environment. Furthermore, the use of mitigation strategies associated with forestry is only concerned with bioenergy and does not discuss the carbon storage potential of timber products. However, the Conference of the Parties to the Kyoto Protocol in Copenhagen in 2009 did recognise the importance of including timber products as carbon sinks, and the 2011 Durban and 2012 Doha conferences stated that carbon stored in wood products should be integrated into reporting procedures.

The environmental benefits of using timber as a substitute for high-embodied-energy construction materials have been demonstrated (e.g. Buchanan and Levine, 1999; Börjesson and Gustavsson, 2000; Gustavsson and Sathre, 2006; Nässén *et al.*, 2012). The advantages of using timber and other bio-derived materials as a means of storing sequestered atmospheric carbon in the built environment have also received attention in the scientific literature (e.g. Pilli *et al.*, 2015). Although the environmental benefits of using natural materials, such as timber in construction, can be clearly demonstrated, the same cannot be said for the economics unless the external costs of climate change are internalised into the material prices. This requires carbon accounting methods to be developed (Sathre and Gustavsson, 2009). Conventional LCA methods do not assign any benefits to the temporary storage of atmospheric carbon because the timing of emissions relative to removals is not considered.

But the impacts of storing atmospheric carbon dioxide are dependent upon the length of time for which the carbon is removed from the atmosphere (Cacho *et al.*, 2003; Levasseur *et al.*, 2013). This has been taken into consideration in the UK Publicly Available Specification 2050 (*PAS* 2050, BSI, 2008) and the European Commission's International Reference Life Cycle Data (*ILCD*) Handbook (Wolf *et al.*, 2012). With PAS 2050, the benefits of carbon storage are calculated based on a weighted time average approach for an assessment period of 100 years. For example, if a bio-derived product containing 1 kg of atmospheric carbon is used in a building for 50 years before disposal by incineration, then the benefit of carbon storage is calculated as $(50/100)\times 1 = 0.5$ kg. The ILCD methodology considers biogenic carbon sequestration as a negative value and emissions as a positive value. The carbon credits in biogenic materials arise from the effect of delayed emission over a 100-year assessment period. If the emission of 1 kg carbon is delayed for a period of 50 years, this is calculated as $(50/100)\times 1 = 0.5$ kg, in the same way as the PAS 2050 example. The benefits of atmospheric carbon storage in bio-derived products can only be accounted for if the material is derived from a sustainable production source. For the case of timber products, this means that there has to be regeneration of the forest after felling to produce the timber. If felling of the timber results in land-use change (such as conversion to agriculture), then the benefits of atmospheric carbon storage in the HWPs are no longer present, and according to the ILCD guidelines, this biogenic carbon should be treated as if it was fossil carbon. Brandão *et al.* (2013) reviewed six methods (including PAS 2050 and ILCD) for accounting for the impacts of carbon sequestration and the temporary storage and release of biogenic carbon. The paper identified that the benefits of carbon storage are highly dependent upon the time horizon adopted and that this is based upon value judgements rather than having any sound scientific basis. As such, the timeframe adopted is informed by policy considerations, and the commonly used 100-year period for global warming potential (*GWP*) calculations is based upon the desire to bring about achievable change in a crucial period in the history of humanity. The intention is to change behaviour to a sustainable development trajectory.

Although many studies of carbon storage in HWPs have been conducted, there are no commonly recognised methods for determining and reporting this in bio-derived products from a time perspective. PAS 2050 and ILCD give two methods for dealing with the temporal factor, but other approaches have been suggested. The method of Moura-Costa and Wilson (2000) calculates a sequestration-based equivalence factor called the absolute global warming potential (*AGWP*). The AGWP is defined as the cumulative radiative forcing potential for $CO_2$ of unit mass over a specified time horizon. This is calculated from the following relationship:

$$\text{AGWP} = \int_0^{\text{TH}} a_x \cdot \left[C(t)\right] \mathrm{d}t \tag{9.1}$$

where *TH* is the time horizon under consideration, *t* is time, $a_x$ is the radiative forcing due to the presence of unit mass of $CO_2$ in the atmosphere and $C(t)$ is the concentration of a pulse of $CO_2$, decaying as a function of time, which is usually expressed in terms of the Bern model. Based upon these considerations, they found that removing 1 tonne of $CO_2$e from the atmosphere and storing it for 55 years counteracts the effect

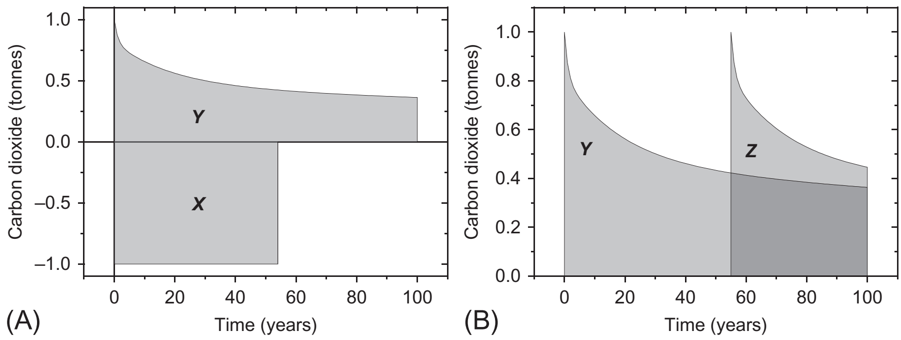


**Fig. 9.1** Illustration of the Moura-Costa (A) and Lashof (B) methods for calculating the benefit of carbon storage. In (A), a pulse of 1 tonne of carbon dioxide is released into the atmosphere, and this decays according to the Bern mechanism. The total global warming potential (GWP) over 100 years is represented by the area under the curve. The same total GWP is represented by storage of 1 tonne of $CO_2$ for 55 years ($X=Y$). In (B), the carbon is stored for 55 years and then released as a pulse of $CO_2$. The total GWP is the area under the curve *Z*; the benefit of storage is given by subtracting *Y* from *Z*.

of releasing a pulse of $CO_2$ into the atmosphere with a residence time of 100 years. This method allows for benefits greater than 100% if the 55-year storage period is exceeded. Another approach, referred to as the Lashof method, assumes that the storage of atmospheric $CO_2$ is equivalent to a delayed emission of fossil $CO_2$, but the carbon tracking is performed in the atmosphere rather than the biosphere (Fearnside, 2002; Fig. 9.1).

Levasseur *et al.* (2013) examined the problem of GWP impact using a traditional LCA approach without including sequestered carbon, a traditional approach including sequestered carbon, PAS 2050, ILCD and dynamic LCA methodologies. Each approach gave different results, there were dramatic differences in some cases. It was concluded that the dynamic LCA approach was the preferred method for providing reliable data, although the results obtained were heavily dependent upon the assumptions made and the time horizon considered. The study also examined the problem using a functional unit of a wooden chair, which can give different results compared with studying temporal carbon storage of a pool of HWPs. A pool of biogenic carbon products does not release carbon to the atmosphere in a pulse, as is the case with a single product, but in a manner that is better modelled as a probability distribution (Shirley *et al.*, 2011). Many studies investigating the release of carbon from HWP pools have modelled this behaviour as a single-exponential decay (as in the IPCC guidelines), but Shirley *et al.* (2011) pointed out that this does not adequately consider that the probability of a product being taken out of service is related to the age of that product. This was dealt with by the development of a distributed decay model (Marland and Marland, 2003; Marland *et al.*, 2010), which uses a probability distribution to determine how much of production from a particular year decays in any given time interval. This type of model is analogous to the approach adopted by the life assurance industry in actuarial mathematics. This form of modelling is very useful when attempting to adopt a realistic methodology for pricing carbon and assigning a value to the cost of emissions from the HWP pool in the future.

The carbon pool of HWPs can be in one of three states, stable, increasing or decreasing. Which one of these applies obviously depends upon the rate at which harvested wood enters the pool and the rate that the carbon in the pool is oxidised. Although a huge amount of atmospheric carbon is stored in wood products, this is of no significance from the point of view of mitigation if the carbon stock is stable. Indeed, the assumption that wood is immediately oxidised after harvesting is mathematically identical to a stable stock of HWPs. If the size of the pool is decreasing, then this means that more biogenic carbon is being released than is entering, which will result in an increase in atmospheric radiative forcing, as is the case with the burning of fossil fuels. From this perspective, it is irrelevant whether the source of the carbon is biogenic or fossil; it is the fact that the stock in the HWP pool is decreasing that is important. Conversely, an increase in the size of the GWP pool is of benefit, since this results in a net sequestration of atmospheric carbon, provided the amount of carbon stored in the forests from which the wood is derived either is stable or is increasing. This means that the timber has to come from sustainably managed forests. The HWP pool size can be increased by raising the amount of wood harvesting and/or by increasing the lifespan of wood products in the HWP pool (increased levels of recycling, improved durability, etc.). The best overall strategy is to increase the level of HWPs and other biogenic materials in the pool as well as increasing the retention time through extending the life of products (enhanced durability) and by adopting a cascade material management structure. Finally, the biogenic carbon can be returned to the atmosphere by incineration with energy recovery, thereby obtaining credits for substituting a fossil fuel source.

This section has considered how the various methods account for the temporal carbon dynamics, and there is also a section focusing on the single product versus the pool perspective. In addition, it is noted that the influence of the choice of spatial system boundaries and the land-use baseline or land-use reference system is of importance in carbon accounting studies. There is insufficient scope to review this topic thoroughly, and readers are directed to multiple authors on this topic (Cherubini *et al.*, 2013; Berndes *et al.*, 2013; Soimakallio *et al.*, 2015; Brander, 2015; Røyne *et al.*, 2016; Penaloza *et al.*, 2016).

Unfortunately, at the time of writing, the situation regarding the methodology of measuring and accounting for carbon in biogenic products is not satisfactory. Although the ILCD methodology is still current, there have not been many useful developments in standardisation. Although the 2008 version of PAS 2050 did include methods for calculating the temporal aspects of biogenic carbon storage in annex C, by the time that the 2011 version had been published, this was no longer present. The European Standard EN 16485 (CEN (2014b)) giving product category rules (PCR) for round and sawn timber featured a temporal calculation method for determining the storage of biogenic carbon in the draft form, but in the final published version, this had been removed. This is a situation that cannot be allowed to continue and urgent action is required.

### 9.2.3 Circular economy, bio-economy, and low-carbon economy

The expectations and needs of increasingly bio-based building materials are part of a greater transition of our society towards a more bio-based one. In recent years, this endeavour has been embodied in and gained momentum through the emergence of concepts such as 'circular economy', 'bio-economy' and 'low-carbon economy'. The emergence of these concepts is, for example, shown in their increased use in the scientific literature in the past 10 years (Fig. 9.2). Below, we introduce these concepts and discuss how they relate to bio-based building materials.

#### 9.2.3.1 Circular economy

An early notion of the need for a circular economy was that of Kenneth E. Boulding in his essay 'The economics of the coming spaceship Earth' (Boulding, 1966). Boulding argues that economists ought to increasingly treat the Earth as a closed system—thus his analogy between humanity and a spaceman living in a spaceship—in contrast to an open system for which he uses the analogy of a cowboy, which has 'illimitable plains' at his disposal. In a closed system, 'the outputs of all parts of the system are linked to the inputs of other parts' (Boulding, 1966). He recognises that economists at the time, however, viewed the world as an open system in which matter, energy and information are seen as entering the system from somewhere else (i.e. there is a seemingly endless supply of natural resources) and leaving the system to somewhere else (i.e. there is a

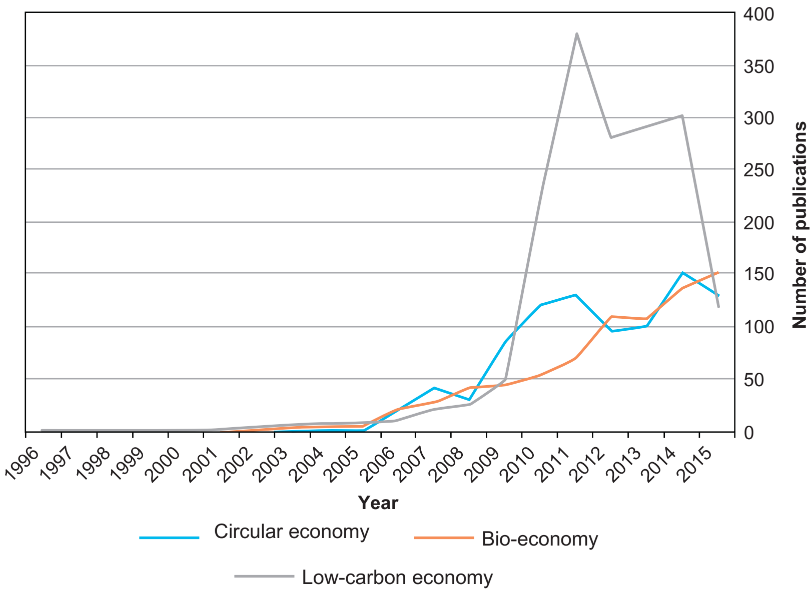


**Fig. 9.2** Number of publications found in a search amongst article titles, abstracts and keywords, in the Scopus database of peer-reviewed literature, 5th of Mar. 2016, using the keywords 'circular economy'; 'bio-economy', 'bioeconomy', 'bio-based economy' or 'biobased economy'; and 'low-carbon economy' or 'low carbon economy'.

seemingly endless capacity to absorb waste). He concludes that 'the closed earth of the future requires economic principles which are somewhat different from those of the open earth of the past' in which 'man must find his place in a cyclical ecological system which is capable of continuous reproduction of material form even though it cannot escape having inputs of energy'. This is precisely the idea of the circular economy: closing the material loops within the Earth system, so that waste is used as an input to new productive processes, directly between human activities or via natural processes—for example, $CO_2$ emissions from incineration of bio-based materials are absorbed by growing biomass, which then is harvested and incorporated in new materials—fuelled by the only abundant energy flow entering the Earth system, solar radiation (directly or via air and water moving because of solar radiation). This is in stark contrast to the still prevailing 'linear' economy, also referred to as a 'take-make-waste' economy.

Although the circular economy concept has been present in the literature since Boulding's work in 1966 (Stahel and Reday-Mulvey, 1981; Pearce and Turner, 1989), it has not received widespread attention until the recent years, as sustainability issues associated with the predominant linear economy have become increasingly apparent. Two developments have particularly put the circular economy in the spotlight. The first was when China adopted circular economy as a development strategy in 2002 (Yuan and Morgiguchi, 2008) and then made it part of its national policy in the 11th five-year plan issued in 2006 (Zhijun and Nailing, 2007). This explains the increase of scientific publications on the topic starting in mid-2000 (see Fig. 9.2; the Chinese context is a remarkably common theme for many of the publications found in the literature search).

The second development that notably increased the interest in the circular economy concept is when the solo long-distance yachtswoman Ellen MacArthur in partnership with five multinational corporations launched the Ellen MacArthur Foundation in 2010. The charity foundation declared a mission to 'accelerate the transition to a circular economy' and developed the first coherent framework around the concept (Ellen MacArthur Foundation, 2015). In the recent years, this framework has shaped discussions in industry and media pertaining to the circular economy. The framework defines a circular economy as 'a continuous positive development cycle that preserves and enhances natural capital, optimises resource yields and minimises system risks by managing finite stocks and renewable flows' (Ellen MacArthur Foundation, 2015). Furthermore, the framework emphasises that, in a circular economy, all energy flows should be renewable and material flows belong to either one of two types: biological nutrients (i.e. biotic materials designed to enter the biosphere safely) and technical nutrients (i.e. materials that are designed to circulate in the technosphere without entering the biosphere). Also, the framework emphasises the importance of managing stocks of materials by sharing, reusing, remanufacturing and recycling, and the importance of managing renewable material flows by preserving and enhancing natural capital (e.g. soil quality) and by cascading (i.e. using a given resource for several subsequent functions before it re-enters the biosphere). Finally, the framework emphasises the need for 'revealing and designing out negative externalities', further described as 'reducing damage to human utility, such as food, mobility, shelter, health, …', and managing land use; air, water and noise pollution; release of

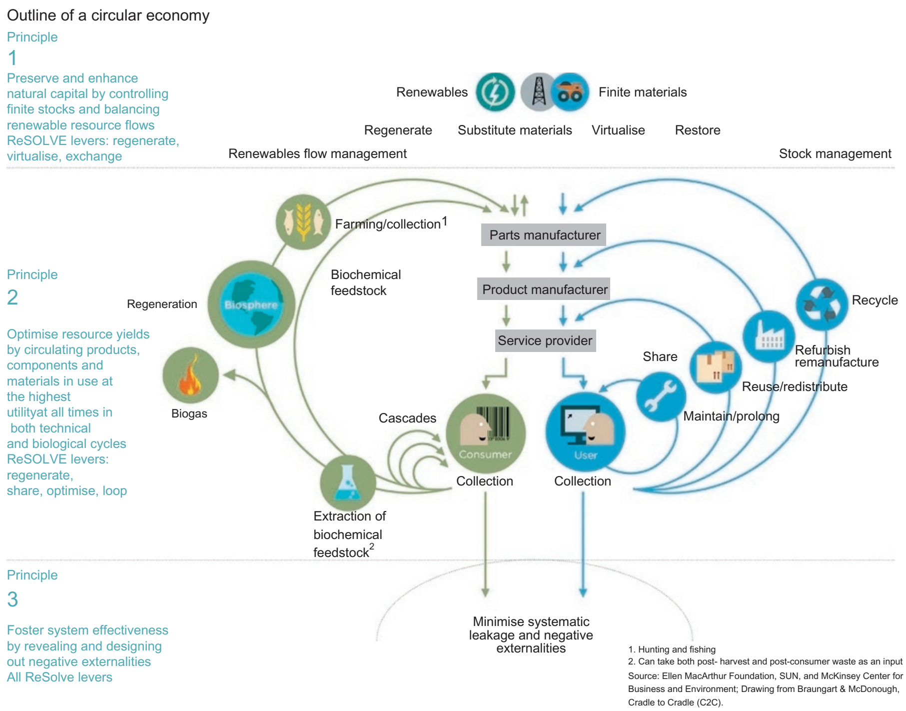


**Fig. 9.3** Outline illustration of the circular economy.
Reproduced with permission from the Ellen McArthur Foundation.

toxic substances; and climate change (Ellen MacArthur Foundation, 2015). Fig. 9.3. summarises the building blocks of the circular economy framework as defined by the Ellen MacArthur Foundation.

Cradle-to-cradle (*C2C*) certification of products is connected to the term circular economy as one of the material quality categories is material reutilisation alongside material health, renewable energy and carbon management, water stewardship and social fairness.

For further reading about the circular economy, we recommend the literature review by CIRAIG (2015). Amongst others, the review reveals the connections between circular economy and other, associated concepts, such as the green economy, life cycle thinking and industrial ecology.

### *9.2.3.2 Bio-economy*

As seen in Fig. 9.2, the concept of a bio-economy (also referred to as a bio-based economy) has also gained momentum in the scientific literature in the past 10 years, most probably because the replacement of fossil resources with bio-based resources is seen as an important means for reducing GHG emissions and dependencies on imported, fossil resources. It has been said that ‘the bio-based economy can and should be to the 21st century what the fossil-fuel-based economy was to the 20th century’ (Hardy, 2002).

The intention of transitioning to a bio-economy is present also in the political arena. For example, in 2012, the European Commission adopted a bio-economy strategy as a means for addressing the environmental, energy, food supply and natural resource challenges that Europe and the world are facing (European Commission, 2012). In the strategy, the bio-economy is defined as ‘the production of renewable biological resources and the conversion of these resources and waste streams into value added products, such as food, feed, bio-based products and bioenergy’. The European bio-economy strategy has, amongst others, strongly influenced the EU framework for funding research and development, Horizon 2020 (European Commission, 2016). In addition, national bio-economy strategies have been developed, for example, in the United States, Canada, Australia, South Africa, Finland, Germany and Sweden (Ingrao *et al.*, 2016). The Swedish strategy for a transition to a bio-economy is described in the following way: ‘the conversion to a bio-based economy entails switching from an economy largely based on fossil resources to a more resource-efficient economy based on renewable resources that are produced through using sustainable soil- and water-based ecosystem services’ (VINNOVA, 2013). The term bio-economy is not, however, as prevalent in political and strategic documents as one might think. This is seen in the background material to the report ‘The use of concepts related to sustainable development in political and strategic documents’ (Fahnestock, 2016a) in which the prevalence of 217 concepts in 110 documents was assessed, and ‘bioeconomy’ was ranked as the 199th most frequently used concept with only 14 mentions (Fahnestock, 2016b).[1] It should be noted that the term bio-economy often refers to different things in Europe and in the United States: In Europe, it is a very broad term, as described above, whereas in the United States, the term often refers more specifically to the increased use of synthetic biology in society (Scarlat *et al.*, 2015).

Compared with the Ellen MacArthur Foundation framework for a circular economy, the bio-economy is much less of a complete concept in terms of being a comprehensive solution for addressing environmental concerns. Just increasing the use of biological resources does not guarantee a more sustainable society. Therefore, the development of a bio-economy must be combined with careful consideration of the many pressures threatening ecosystems worldwide—which are at risk of being harmed by increased harvesting of bio-based resources—including unsustainable land and water management practices and the subsequent impact on biodiversity. Some policy frameworks advocating a bio-economy do include such consideration as an inherent part of the definition of a bio-economy (e.g. the above definition in the Swedish national strategy), whereas others do not. It should be noted that this previously has been the case also for the circular economy concept, which, through the development of the Ellen MacArthur Foundation framework, was made more coherent and comprehensive, addressing not only material and energy use but also other concerns. Because of the narrow focus on the use of bio-based resources, the bio-economy can be interpreted as a subset of the circular economy.

[1] In the studied documents, ‘low carbon’ is the 69th most frequently used concept, with 887 mentions, and ‘circular economy’ is the 129th most frequently used concept, with 175 mentions.

### 9.2.3.3 Low-carbon economy

The concept of a low-carbon economy (also referred to as a decarbonised economy) has emerged as a means for addressing climate change. A low-carbon economy is simply an economy that causes low levels of GHG emissions compared with today's carbon-intensive economy. 'Carbon' refers to carbon dioxide, the GHG, which contributes the most to climate change. The low-carbon economy can be seen as a step in the process towards a zero-carbon economy.

Just as the bio-economy, the low-carbon economy is a narrow concept compared with the circular economy concept, as its coverage is limited to one parameter of a future sustainable society. In contrast to the bio-economy, the low-carbon economy is, however, more focused on reducing environmental impact rather than on promoting a certain solution for achieving the reduction. That is, the low-carbon economy is rather a goal than a means or strategy for reaching the goal. Both the bio-economy and the circular economy concepts give more guidance for how to reach goals. This difference is reflected in policy frameworks. For example, the European Commission has set a goal to develop a low-carbon economy by 2050, a development in which the bio-economy is expected to play a significant role (Scarlat *et al.*, 2015).

### 9.2.3.4 Circular economy, bio-economy and low-carbon economy in relation to bio-based building materials

From the above descriptions, it is clear that bio-based building materials are potentially an important component in the circular economy, bio-economy and low-carbon economy. In particular, bio-based building materials are by necessity a fundamental part of a bio-economy, considering that building materials represent such a large share of the materials produced and used in society—about 40% (Roodman and Lenssen, 1995). It is also difficult to envision a low-carbon economy without a substantial share of bio-based building materials, as such materials in general give rise to lower GHG emissions compared with other, functionally equivalent building materials (Werner and Richter, 2007; Salazar and Meil, 2009; Pajchrowski *et al.*, 2014). Although such comparisons to some extent depend on the chosen assessment method and uncertain parameters in the material life cycle, studies indicate that bio-based materials are often a preferable choice even when such aspects are accounted for (Sandin *et al.*, 2014; Røyne *et al.*, 2016).

Increased use of bio-based building material is probably also important for developing a circular economy, although abiotic materials may play a greater role in such an economy compared with a bio-economy or a low-carbon economy. However, for bio-based building materials to be part of a circular economy, it is important that (i) the material origin from regenerative agricultural or forest land managed in a way that avoids negative externalities; (ii) land management, harvesting and further processes in the material life cycles are fuelled by renewable energy and (iii) the materials are designed in a way that allows them to safely re-enter the biosphere at their functional end of life, which means that biological and technical nutrients that are combined (e.g. in composites) must be possible to separate and that toxic substances (e.g. used for preservation or fire protection purposes) must be degraded at end of life (e.g. through incineration).

## 9.3 Measurement and certification

To provide clarity to enable informed choices to be made of low-impact construction materials and products, it is essential to have a robust and consistent means of measuring, attributing impacts and certification of the construction products and the construction assets lifecycle environmental impacts.

### *9.3.1 Environmental profiles and eco-labels*

#### *9.3.1.1 Different types of eco-labels*

Environmental labels are an internationally recognised means of communicating the environmental credentials of products in response to consumer demand for information. Different labels take different assessment approaches, but the common goal is to present verifiable and accurate information and to promote products and services that have potentially less impacts on the environment by aiding buyers to make better informed choices. Environmental labels are voluntary and are developed under the ISO 14020 (ISO (2000)) series of standards and fall under three classes: Type I, Type II and Type III, with the series of standards setting out the guiding principles for the development of environmental labels and declarations (Allison and Carter, 2000).

This section provides a short description of each of the three different types of labels, the standards they are related to within the ISO 14020 (ISO (2000)) series and examples of how these labels apply to bio-based products, with particular focus on Type I and Type III environmental labels. Drivers for the use of these labels are also provided in this section.

##### Type I—Ecolabels

This is an environmental label established under the requirements of ISO 14024 (ISO (2004)). Type I labels are based on a pass-fail multicriteria approach devised to indicate the overall environmental performance of a product. If one of the criteria is not met, the product will not be awarded a label. Commonly referred to as 'eco-labels', Type I environmental labels are provided by programmes set up and operated in line with the requirements of ISO 14024 (ISO (2004)). Eco-labels are third-party verified and are typically simple documents that convey basic relevant environmental information. Many national eco-labels have evolved with at least 40 being actively used on construction products across the globe from Israel to India and Hong Kong to Hungary.

##### Type II—Self-declared environmental claims

Type II environmental labels are defined as 'self-declared' environmental claims made by manufacturers and businesses. Guided by ISO 14021 (ISO (2016)), the claimant can declare the environmental quality of their product, without set criteria, nor benchmarks, nor quality checks. However, this declaration should be verifiable and must not be misleading. Other restrictions include the avoidance of vague or ambiguous claims such as 'environmentally friendly' or 'more sustainable'. Verifiable terms such as 'made from x% recycled material' are permitted.

### Type III—Environmental declarations based on LCA

Referred to as EPD, Type III environmental labels are defined by ISO 14025 (ISO (2006a)) and are third-party verified under established programmes. Prepared from LCA using predetermined criteria-set rules, EPD are typically more complex compared with eco-labels as they contain a range of information from various aspects of the product supply chain. Type III labels are comparable with nutritional labels on food products and can be used for product comparison under strict guidelines dictated by relevant standards. Type III labels for construction products are further governed by specific standards at both the international and European level (ISO 21930, ISO, 2007; EN 15804, CEN, 2012b, respectively), and the LCA studies are according to the ISO 14040 (ISO (2006b)) series of standards. Type III labels are best suited to communicating environmental credentials of products to businesses or public bodies, because they give more comprehensive information on a product than Type I and Type II, and the outputs have been interpreted.

## *9.3.1.2 Type I—Ecolabels*

### Examples of the main ecolabels

Blue Angel (2013) is the first worldwide eco-labelling system. Created in 1978 on the initiative of the German Federal Minister of the Interior, the Blue Angel predates the ISO standard for Type I eco-labelling standard and now covers around 12,000 products and services in more than 100 product categories. Criteria are developed for each individual product group, which must be fulfilled to be awarded with the Blue Angel mark. The requirements set by the eco-label focus on the impacts that products have on the climate, resources, water, soil, air and people. The label is owned by the German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety.

The Nordic Ecolabel (also referred to as the Nordic Swan) is the official eco-label of the Nordic countries (Iceland, Norway, Sweden, Finland and Denmark). It was introduced in 1989 by the Nordic Council of Ministers to support a more sustainable production and consumption. Currently there are 63 product groups within the Nordic Ecolabel, each with their own set of criteria but considering the same important environmental issues (energy usage, climate aspects, water usage, source of raw materials, use of chemicals, hazardous effluents, packaging and waste).

Introduced in 1991, NF environment is the French eco-label scheme. It is issued by AFNOR Certification (part of AFNOR Group) or a certification body mandated by AFNOR Certification. In order to be awarded this eco-label, products must comply with environmental and social requirements. Just like the Nordic Ecolabel, these criteria are not identical across the 61 products and service groups currently covered.

EU Ecolabel is the eco-label scheme set up by the European Commission. It was established in 1992 and now includes 35 categories for more than 10,000 products. As the only label recognised throughout Europe, it encourages businesses to market products and services that cause less impacts on the environment.

### Examples of requirements for bio-based products

Using the Blue Angel Ecolabel as an example, this section looks at how wood products are covered in Type I eco-labelling. In Blue Angel (2013), wood products are divided into three categories:

- Composite wood panels that include fibreboards, wood-core plywood, chipboards and veneer plywood boards.
- Wood products, products such as furniture or slated frames.
- Floor coverings, panels and doors.

Table 9.1 illustrates the requirements for wood floor covering products in the Blue Angel Ecolabel. These requirements are prescribed in several sections, which cover the different life cycle stages of a product and the communication of the label. Most of the requirements are compulsory, meaning they must be met and verified by a third party before the label is awarded.

Wood floor coverings are considered in a number of Type I eco-labels. While all labels have their particular focus [e.g. the EU Ecolabel scheme is the only one to refer to genetically modified wood and prohibit it (European Commission, 2010)], some of the requirements are common to most labels (e.g. the origin of wood, provenance from sustainably managed forest). However, whilst some of the requirements appear very similar, there may be variations in the calculation methods or performance levels. For instance, for the energy consumption requirements, the calculation method is different between the Nordic Swan and EU Ecolabel, as well as the limit value set by the respective documents. The results of the assessment are therefore not comparable, and a product that passes the requirements of one label may not meet the requirements of another.

**Table 9.1 Requirements for wood floor coverings in Blue Angel Ecolabel (2013)**

| Section | Requirement | Level |
|---|---|---|
| Manufacture | Understand the origin of the wood<br>• 100% from legal sources<br>• >50% by weight from sustainable forest | Compulsory |
| | Do not exceed the limit value for formaldehyde in wood-based materials | Compulsory |
| | Prohibit the use of carcinogenic, mutagenic and reprotoxic (*CMR*) substances | Compulsory |
| | Do not exceed the limit value of VOC emissions from the coating systems | Compulsory |
| Use | Do not exceed the limit values of emissions for indoor air quality | Compulsory |
| | Carry out an odour test | Optional |
| | Ensure that packaging is designed to allow the outgassing of volatile components | Compulsory |
| | Be sure that product meets serviceability requirements | Compulsory |
| Recycling and disposal | Prohibit the use of halogenated organic compounds in the manufacture of the product | Compulsory |
| | Only use the flame retardants listed | Compulsory |
| | Prohibit the use of biocides | Compulsory |
| Declaration and consumer information | Be sure to include the listed information (e.g. name and instruction recommendations) in the product declaration | Compulsory |
| Advertising messages | Prohibit terms listed in advertising messages | Compulsory |
| | Prohibit terms listed, such as 'organic' or 'eco' to describe product attributes | Compulsory |

### *9.3.1.3 Type II—Self-declared environmental claims*

Type II environmental labels are not considered in any more detail here as they are highly variable and defined as 'self-declared' environmental claims made by manufacturers and businesses.

### *9.3.1.4 Type III—Environmental declarations based on LCA*

An EPD is a declaration based on third-party verified LCA. The LCA and the verification and issue of a construction product EPD are carried out in accordance with applicable international standards that set out the framework, principles, requirements and rules (ISO 14025 (ISO, 2006a); ISO 14040, (ISO, 2006b); ISO 14044 (ISO, 2006c); ISO 21930 (ISO, 2007)). The LCA result presented in an EPD is a table of values in different units of measurement that represent different environmental impact indicators. There is no pass or fail criteria, so having an EPD is not necessarily a representation or mark of 'good' or 'bad' environmental performance but simply a measure of performance. A number of EPD programmes or schemes for construction products have been developed across the world in accordance with the relevant standards mentioned.

The broad nature of these standards allowed interpretations, which meant that varying results were generated based on the same standards for the same product from different practitioner sources. Such differences potentially extended to the environmental indicators reported, and different environmental indicators could be used by different schemes. So, in 2004, in order to harmonise the development of EPD in Europe, the European Committee for Standardisation (CEN) set up Technical Committee 350 (CEN/TC 350, CEN, 2012a). The committee focused on three aspects (environmental, social and economic) and developed standards for the assessment of construction products (the product level) and for whole buildings (the building level). From the committee work, a European standard for construction products EPD was published (EN 15804, CEN, 2012b). EN 15804 (CEN (2012b)) is much more prescriptive than ISO 21930 (ISO (2007)), defining the approach to follow, the indicators to be declared and which stages of a product life cycle and processes need to be included. Table 9.2 provides the list of impact indicators that need to be included in an EN 15804 (CEN (2012b)) EPD.

There are three main types of EPD: cradle-to-gate, cradle-to-gate with options and cradle-to-grave, shown in Fig. 9.4, adapted from CEN (2012b). This modular approach allows the optional selection of different life cycle stages (known as information modules) relevant to the owner of the declaration, the intended user of the declaration or the user of the product concerned.

For wood and wood-based products, an additional standard has been developed by the Technical Committee CEN/TC 175 rand sawn timber. This standard, EN 16485 (CEN (2014b)), complements the rules defined in EN 15804 (CEN (2012b)) and is therefore used in conjunction with EN 15804 (CEN (2012b)). Using EN 16485 (CEN (2014b)), aspects relevant to the specific product category (wood) are considered, such as the renewability of wood and its potential carbon neutrality, carbon storage, energy and water content of wood. Further, in order to harmonise the quantification of the potential benefits associated with carbon storage in wood and wood-based products, an LCA calculation method (EN 16449, CEN, 2014a) has also been published.

#### *9.3.1.5 How to obtain an EPD in Europe*

EPD are verified and issued by EPD schemes or programme operators (*PO*). There are several PO in Europe, typically one in each country or region. Examples of established PO include BRE (the United Kingdom), IBU (Germany) and AFNOR (France). EPD programmes are membership based, so the first step in obtaining an EPD is identifying and joining an appropriate programme (Construction Products Association, 2012).

The LCA for deriving the data for the EPD needs to be carried out by an LCA practitioner using appropriate PCR. The programme will either develop a PCR or select an existing PCR (which is an interpretation of EN 15804, CEN (2012b)), developed in accordance with ISO 14025 (ISO (2006a)) by an expert group including manufacturers and other stakeholders and is peer reviewed, and the entire development process is moderated by a PO. A valid PCR should be publicly available and published on the

**Table 9.2 EN 15804 (CEN (2012b)) environmental impact indicators**

| | Indicator | Unit |
|---|---|---|
| Impact assessment | Global warming potential, GWP | kg $CO_2$ equiv |
| | Depletion potential of the stratospheric ozone layer, *ODP* | kg CFC 11 equiv |
| | Acidification potential of land and water, *AP* | kg $SO_2$ equiv |
| | Eutrophication potential, *EP* | kg $(PO_4)_2$ equiv |
| | Formation potential of tropospheric ozone photochemical oxidants, *POCP* | kg Ethene equiv |
| | Abiotic resource depletion potential for elements, *ADP* elements | kg Sb equiv |
| | Abiotic resource depletion potential for fossil fuels, ADP fossil fuels | MJ, net calorific value |
| Resource use | Use of renewable primary energy excluding energy resources used as raw material | MJ, net calorific value |
| | Use of renewable primary energy resources used as raw material | MJ, net calorific value |
| | Use of nonrenewable primary energy excluding primary energy resources used as raw material | MJ, net calorific value |
| | Use of nonrenewable primary energy resources used as raw material | MJ, net calorific value |
| | Use of secondary material | kg |
| | Use of renewable secondary fuels | MJ |
| | Use of nonrenewable secondary fuels | MJ |
| | Net use of fresh water | $m^3$ |
| Waste | Hazardous waste disposed | kg |
| | Nonhazardous waste disposed | kg |
| | Radioactive waste disposed | kg |
| Output flows | Components for reuse | kg |
| | Materials for recycling | kg |
| | Materials for energy recovery (not being waste incineration) | kg |
| | Exported energy | MJ for each energy carrier |

PO's website. Some PO, such as IBU, have specific PCR for specific product groups, and others, such as BRE, have one PCR covering all construction products.

The LCA study can be done either in-house (if the appropriate expertise is available) or externally using a consultant. The study is carried out using appropriate software or tools—the PO can provide guidance on the best approach to take. Some POs have launched online LCA tools to provide access to data and a route to EPD for a much wider audience than has been possible before, for example, BRE LINA www.bre.co.uk/lina

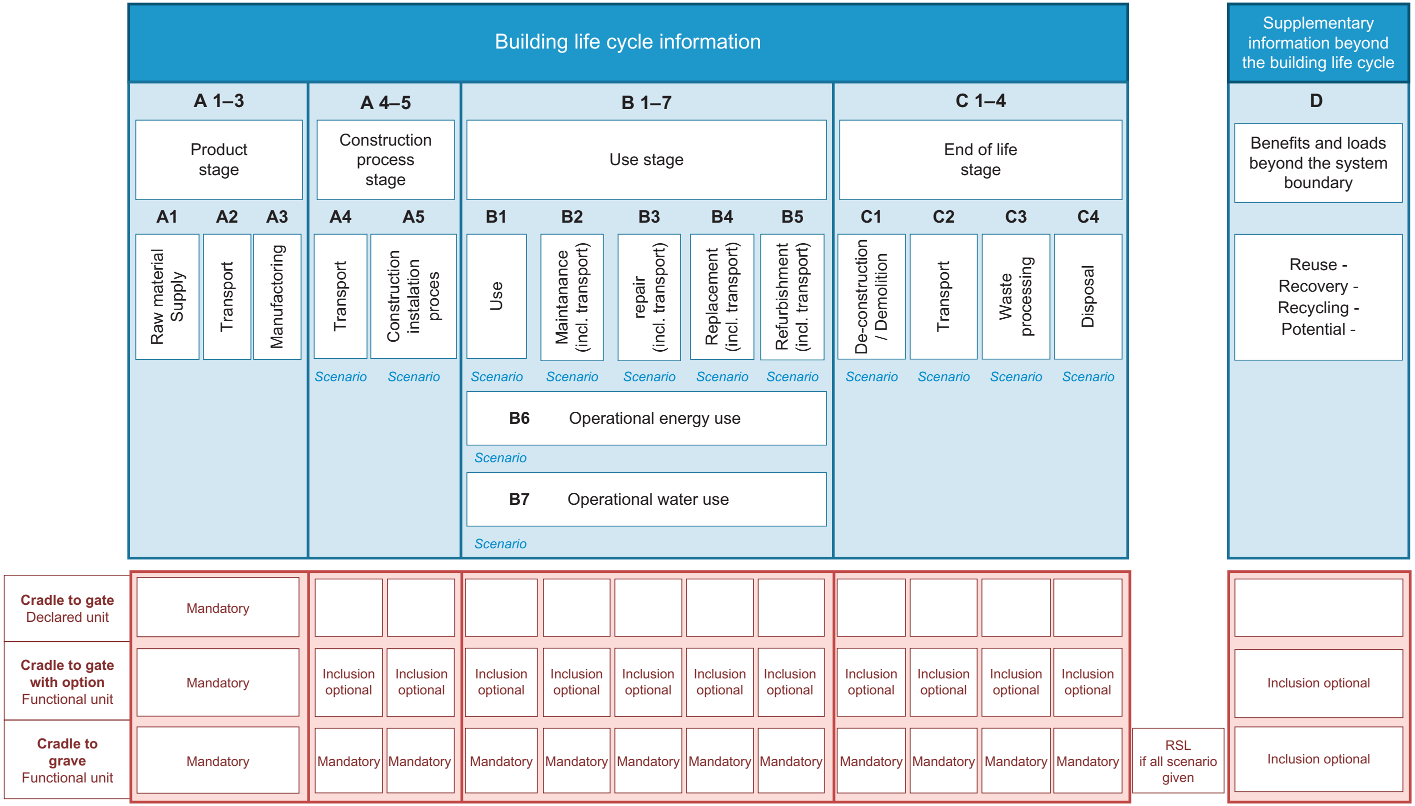


**Fig. 9.4** Boundaries of the study for cradle-to-gate, cradle-to-gate with options or cradle-to-grave.

The completed LCA study results are then verified by a qualified verifier external to the study (this is the 'third-party' verification) usually appointed by the programme. The verification process checks the information presented in the EPD and the study as documented in an LCA report for issues including compliance with standards, plausibility and compliance with the programme rules. The verifier determines if the EPD is suitable or not for issue by the programme, and the PO puts in place measures for final approval and the resolution of disputes. The entire process of independent verification assures that the EPD is robust and it is a transparent declaration that is fit for purpose. Following successful verification, the EPD is issued by the programme and published on a public listing service provided by the PO (typically, the PO's website, e.g. BRE EPD, is published on the GreenBookLive website www.greenbooklive.com). EPD are valid for 5 years, as dictated by EN 15804 (CEN (2012b)), and it is the responsibility of the PO to ensure its website is up-to-date, whilst the owner of the EPD ensures that the published EPD is representative of the actual product throughout the validity of the EPD.

In terms of content of the EPD, EN 15804 (CEN (2012b)) defines what information must be included in an EPD, but the overall look is at the discretion of the PO and, to some extent, the owner of the EPD. Examples of existing EPD of wood products are provided in Fig. 9.5.

### *9.3.1.6 Examples of certifications*

Table 9.3 provides a summary of EPD programmes in Europe. Most of these schemes have been operating for many years, and their schemes have evolved as the standards have changed. All offer EN 15804 (CEN (2012b)) EPD.

Although EN 15804 (CEN (2012b)) provides a more harmonised approach to developing EPD for construction products, it does not yet provide full recognition amongst the scheme operators. In 2011, the EPD programmes from Sweden, Spain, Portugal, Poland, Norway, the Netherlands, Italy, Great Britain, Germany, France and Finland therefore established an international nonprofit association known as the ECO Platform. It is a group of PO, LCA practitioners, industrial associations and other stakeholders with a primary objective of developing a common European framework for EPD based on ISO 14025 (ISO (2006a)) and EN 15804 (CEN (2012b)). The ECO Platform EPD should be applicable across Europe. Covering over 80 product categories, more than 350 products have been certified since 2012.

### *9.3.1.7 Drivers*

This section explores the drivers that make businesses choose to obtain voluntary environmental labels—EPD in particular—for their products. The main drivers identified are building-level assessment, Conformité Européenne (*CE*) marking and country-specific approaches.

## Whole building assessment methods

There are several building-level assessment methods used in Europe. The most popular ones are *BREEAM* (Building Research Establishment Environmental Assessment Methodology), *LEED* (Leadership in Energy and Environmental Design), *HQE* (Haute Qualité Environnementale) and *DGNB* (Deutsche Gesellschaft für Nachhaltiges Bauen). These are described in more detail in Section 9.3.2 including how they promote the use of EPD.


**Fig. 9.5** Examples of environmental product declarations (EPD) for wood products including a Medite MDF product and a Protec treated timber landscaping product.

*(Continued)*


**Fig. 9.5, Continued**

## CE Marking

From 1 Jul. 2013, according to the Construction Products Regulation (*CPR*), it has become mandatory for all construction product manufacturers in Europe to draw up a declaration of performance and apply CE marking. This applies to any construction products that are covered by a harmonised European standard (*hEN*) or conform to a European Technical Assessment, which has been issued for it, when the product is placed on the market. This is a significant change as a CE mark under the provisions of the existing Construction Products Directive (*CPD*) was previously voluntary in most European countries.

The harmonised technical specification for a product defines European Economic Area (*EEA*)-wide methods of assessing and declaring all the performance characteris-

**Table 9.3 Environmental product declaration programmes in Europe**

| | The United Kingdom | Germany | Sweden | France | Norway |
|---|---|---|---|---|---|
| Scheme | BRE EN 15804 EPD | IBU | EPD Environdec | INIES (database)—FDES | EPD Norge |
| Logo | bre | Institut Bauen und Umwelt e.V. | EPD THE INTERNATIONAL EPD SYSTEM | inies | epd |
| Date of creation | 1999 | 2006 | 2007 | 2004 | 2002 |
| Number of categories | All construction products | 41 | 13 | – | 19 |
| Number of EN EPD | >100 | >160 | >30 | >130 | >50 |
| Number of products | | 1456 | 567 | >1600 | 327 |

tics required by regulations in any member state, which affect the ability of construction products to meet seven basic requirements for construction works (*BRCW*):

**(1)** mechanical resistance and stability
**(2)** safety in case of fire
**(3)** hygiene, health and environment
**(4)** safety and accessibility in use
**(5)** protection against noise
**(6)** energy economy and heat retention
**(7)** sustainable use of natural resources

To complete the seventh requirement, the construction works must be designed, built and demolished in such a way that the use of natural resources is sustainable. Stakeholders must also ensure that the construction works, their materials and parts can be reused or recycled after demolition. Whilst BRCW (7) focuses on recycling and the use of LCA, it is not mandatory to have an EPD to fulfil the BRCW (7). However, the CPR has created a system of assessment and verification of constancy of performance, which defines the degree of involvement of the third parties in the process of certification. For a CE mark certification, the degree of involvement must be the highest one (system 1+). It means that the certification shall be carried out by a third party and continuously surveyed and subjected to an audit test. Therefore, because EPDs are third-party verified, requirement related to environmental performance can be fulfilled by EPDs.

## Specific country drivers

While EPD is still voluntary, some countries have decided to promote products that cause less impacts on the environment by setting legislation. These legislations do not specifically require EPD, but EPD can support a manufacturer in meeting the requirements. A few examples of country-specific legislations are provided in this section.

**i.** Belgium

Since 2015, when a manufacturer wants to declare environmental credentials for his product, they shall first carry out an LCA and register the product into the database www.environmentalproductdeclarations.eu, which is a publicly accessible website (SPF Santé Publique, 2015). Moreover, each declaration based on LCA shall be verified by a third party. Because EPDs meet the requirements, they can be used for these environmental declarations.

**ii.** France

The Department of Housing and Urban Planning (*DHUP*) has published a decree (DHUP, 2013) concerning building materials. This decree affects every organisation that wants to put a construction product on the French market and declare their environmental credentials. Therefore, they shall make a complete list of impacts on the environment of the product with a life cycle approach and have a third-party control the quality of these environmental declarations. Thus, Fiches de déclaration environnementale et sanitaire (*FDES*) (EPD) are promoted by this regulation.

The aim of this section was to define environmental labels and to identify the different types: Type I (eco-labels), Type II (self-declarations) and Type III (EPD). Some of the labels are pass/fail (Type I), and others are nutritional (Type III). Both Type I and Type III are third-party verified and can be used to communicate from business to business. While the results from one label to another cannot be compared, much work has been done for the harmonisation and recognition of EPD across Europe, with the introduction of standards such as EN 15804 (CEN (2012b)). Environmental labels are largely voluntary, but drivers such as building-level assessment schemes are rewarding the use of EPD, and as the demand for such scheme increases, the demand for EPD will also increase.

### 9.3.2 Environmental assessment of buildings

The building sector can contribute significantly towards necessary emission reductions with appropriate construction of new sustainable buildings and retrofitting of existing buildings. One strategy for achieving that transformation is most widely known by the term green building. Green building can be characterised as integrated building practices that aim to significantly reduce the environmental footprint of a building in comparison with standard practices. Descriptions of green building generally focus on a number of common elements, especially siting, energy, water, materials, waste and health. One of the most salient features of green building is the integration of many aspects of sustainable building. Although individual elements can be addressed separately, the green building approach is more comprehensive, focusing on the environmental footprint of a building over its life cycle, from initial design and construction to operations during the building's useful life and through end-of-life strategies. The desire to integrate the various elements of green building has led to the development of rating and certification systems for assessing how well a building project meets a specified set of sustainability criteria. Attributes of sustainable buildings with relation to the triple bottom line consist of three categories: environmental, social and economic (Gorse *et al.*, 2016). The environmental attributes include energy and natural resources, water conservation, material use, durability and waste, land use, transport and accessibility and pollution. The social attributes include usability and function, indoor environment conditions (health and wellbeing and architectural consideration), cultural and aesthetic and innovation and design. And the economic attributes include flexibility and adaptability, economic performance and affordability, building manageability and whole life function and value.

### *9.3.2.1 Whole building assessment schemes*

One of the main drivers for manufacturers to create an EPD for their bio-based construction product is that they are rewarded in whole building assessment schemes. Whole building assessment methodologies provide rating schemes that consider the above sustainability attributes in their assessment categories. There are many green building rating systems such as the BREEAM from the United Kingdom, DGNB from Germany, HQE (France) and Green Star (Australia). In the United States, the most popular system is the LEED. In Japan, the Comprehensive Assessment System for Built Environment Efficiency (*CASBEE*) was developed. While each system has unique features, significant overlaps exist amongst them. Sinha and Knowles (2014) compared the assessment categories of four major international green building rating systems: LEED, Green Star, DGNB and CASBEE. The authors concluded that these systems have significant commonalities in their various assessment categories and that the differences are largely in the use and definition of terminology. However, it is important to consider the region-specific developments of the rating systems, which contributes variability to the many rating systems.

#### BREEAM—United Kingdom

Developed by BRE in 1990, the BREEAM was the first building-level assessment method. Today, more than 560,000 buildings have been certified in more than 75 countries, and over 2,200,000 are in the process of being assessed. Two-thirds of the buildings certified in Europe are certified to BREEAM, so more focus has been given here to this building-level assessment method. BREEAM awards a rating (pass, good, very good, excellent and outstanding), which is an overall reflection of the environmental impact of the building. While the scheme has a strong focus on environmental issues, it also covers social and economic aspects of the building. BREEAM covers several issues, such as transport, energy, materials, health and wellbeing, water, management, wastes, ecology and pollution. Depending on the building type, the building life cycle stage and whether it is in the United Kingdom or not, the number of credits awarded for each category and the weighting applied vary. In BREEAM UK New Construction, for example, a weighting of 13%–17% is applied to the materials section, which is quite significant. A number of issues are covered in the materials section: mainly responsible sourcing and environmental impact assessment of materials. More than 50% of the credits are awarded for looking at the environmental impact of materials. BREEAM recognises that the importance of the impact of materials will increase as buildings become more energy-efficient (material consumption and energy use during the operation of the building make up most of the carbon footprint of the building). BREEAM published their strategy for evaluating materials in 2015, and it states that they will continue to reward the use of products with EPD but will also reward a whole building-level assessment approach (in line with EN 15978 (CEN, 2011)).

BREEAM sets the standard for best practice in sustainable building design, construction and operation and has become one of the most comprehensive and widely recognised measures of a building's environmental performance internationally. It encourages designers, clients and others to think about low-carbon and low-impact design, minimising the energy demands created by a building before considering energy efficiency and low-carbon technologies. A BREEAM assessment uses recognised measures of performance in a broad range of categories and criteria from energy to ecology. They include aspects related to energy and water use, the internal environment (health and wellbeing), pollution, transport, materials, waste, ecology and management processes.

## LEED—United States

In 2000, the US Green Building Council (USGBC) launched the LEED certification scheme. The scheme is now present across more than 150 countries, and currently more than 45,000 projects have been certified. The LEED certification process awards building with a medal (bronze, silver, gold or platinum) reflecting environmental impact and outcomes on local communities. LEED covers similar categories to those listed in BREEAM. Since the latest version, LEED v4, the category 'Building Product Disclosure and Optimisation' encourages the use of products with EPD.

## DGNB—Germany

The German Sustainable Building Council (DGNB) scheme was founded in 2007. It is a relatively new scheme, but already more than 1000 projects have been certified or precertified. The scheme awards certified buildings with a gold, silver or bronze medal, which indicates the environmental, economic and social credentials of the building. DGNB categories are similar to those covered in BREEAM, and DGNB encourages the assessment of the materials through the use of a whole building LCA approach. The impact of materials accounts for 14% of the overall DGNB score. The methodology described is broadly in line with EN 15804.

DGNB is a 'second-generation' rating system, giving a more holistic evaluation of the entire life cycle of a building, and adapted schemes are being developed in several countries worldwide. Compared with BREEAM and LEED, DGNB provides more coverage of social and economic attributes. In its scoring system, weights can vary from zero to three (Bedeutungs and Anpassungsfaktor) depending on the system's societal or political relevance and its importance for a specific use profile. Also, an important feature in DGNB is the explicit inclusion of the economy, so that lifecycle costs and stability in value are accounted for in the certificate.

#### HQE—France

The NF HQE Certification was first established in 2004 by the HQE Association and AFNOR Certification. The scheme considers 14 environmental targets, organised in 4 issues (eco-construction, eco-management, comfort and health) and the scores are passable, bien, très bien, excellent and exceptionnel. HQE rewards the use of EPD, but only those produced by Environmental and health reference data for building (INIES), which are Fiches de déclaration environnementale et sanitaire (FDES). Moreover, since 2011, the HQE Association has both the role of owner and manager of the INIES database and promotes even more FDES.

### *9.3.2.2 Sustainability assessment of buildings using EN 15978 (CEN (2011))*

The previous section looked at the environmental assessment of products and mentioned the work carried out by CEN/TC 350 in developing standardised methods for the assessment of the sustainability aspects of new and existing construction works (buildings and civil engineering). This committee has developed standards not only at product level (covering environmental, social and economic issues) but also at building level. In 2012, CEN/TC 350 published a new European Standard for the sustainability assessment of buildings EN 15978 (CEN (2011)). This standard provides guidance to the calculation method, based on LCA (which shall also be ISO 14040 (ISO (2006b)) series compliant), to assess the environmental credentials of buildings. EN 15978 (CEN (2011)) gives the following:

- The description of the object of assessment.
- The system boundary that applies at the building level.
- The procedure to be used for the inventory analysis.
- The list of procedures for the calculations of these indicators.
- The requirements for the data necessary for the calculation.

It takes a similar approach to EN 15804 (CEN (2012b)) in covering all the stages of the building life cycle, and the list of indicators is the same. EN 15978 (CEN (2011)) is based on the data obtained from EPD. EN 15978 (CEN (2011)) also provides the requirements and means to report and communicate the outcomes of the assessment.

The publication of EN 15978 (CEN (2011)) prescribes an LCA approach for the environmental assessment of buildings. However, the approach is one followed mainly by LCA experts as it requires considerable technical knowledge. So, it is important that such a standard is integrated into tools already used by architects and designers to ensure a wider uptake of such an approach at early stages of the building design. Software providers have been working on the development of their existing tools to enhance them with the capabilities to integrate EN 15978 (CEN (2011)) principles. Some of the tools that provide the capability to carry out whole building LCA are now presented briefly.

### IMPACT compliant tools

IMPACT is a methodology and database that can be implemented into tools to make them IMPACT compliant. The methodology and database were launched in 2011 and are the results of a three-year research project conducted by BRE, AEC3, IES Ltd and WD Rethinking. The IMPACT methodology is in line with EN 15978 (CEN (2011)) and allows the integration of LCA data in building information modelling (BIM) type tools. At the time of writing, there are two IMPACT compliant tools: IES-VE and eTool. These tools allow users to calculate the embodied impact of a building and to analyse and improve the building design. The use of IMPACT compliant tools is rewarded in BREEAM.

### Tally

Tally is an application that fully integrated itself in Autodesk Revit software. In 2008, KT Innovations in partnership with Autodesk Sustainability Solutions and Thinkstep began developing Tally as an add-on to Revit, making it is an easy-to-use application for Revit users. By defining relationships between Revit elements and the Tally LCA database, Tally allows the user to quantify the environmental impact of building materials using a building life cycle approach and to compare different design options. Tally is now approved for LEED v4 to achieve Building LCA.

### ELODIE

ELODIE is the French web-software assessing environmental credentials of buildings. It was created in 2006 by the Centre Scientifique et Technique du Bâtiment (CSTB) and the Direction générale de l'urbanisme, de l'habitat et de la construction (DGUHC) and released in the late 2008. ELODIE software provides a solution to the INIES database issues as the FDES were not being used by the construction designers because they were difficult to understand. Because ELODIE is linked with INIES, users can choose a product within the database to model their building. After selecting all the products, ELODIE uses the information contained within the FDES to provide an overall environmental impact of the building. This impact was calculated using the NF (2004) standard, but this has now been withdrawn (August 2016) and, by reference to EN 15978 (CEN (2011)), now EN 15804 (CEN (2012b)), is required. It is compliant with not only HQE that is the French scheme to assess performance of building but also BREEAM.

### Bionova Ltd

One of the construction LCA software leaders has brought an innovative solution to make LCA ‘in a single click’. The solution, One Click LCA, is a cloud-based software that uses information from BIM software (Autodesk Revit, ArchiCAD and Tekla Structures, as long as it uses IFC format) to quickly and easily calculate LCA of buildings. It is linked with the Bionova database that contains verified EPD, publicly available database and allows users to add specific EPD. The software is third-party verified for compliancy with EN 15978 (CEN (2011)), ISO 21931-1 (ISO (2010)), ISO 14040 (ISO (2006b)) and EN 15804 (CEN (2012b)). Furthermore, the software has been officially approved to provide LCA for more than 20 certification schemes (amongst them are LEED v4, BREEAM International, DGNB and HQE).

The construction sector plays a key role in the consumption of energy and resources and in solid waste accumulation; it is important to quantify the environmental performance of buildings to communicate their potential environmental impacts and aspects and their influence on sustainable development.

A building uses most of its energy during its service life, which is dominated by operational energy demands to cool, heat and light the building. This use phase of a building is often said to contribute 70%–90% of its environmental impact (Beccali *et al.*, 2013; Cuéllar-Franca and Azapagic, 2012; Ortiz *et al.*, 2010; Citherlet and Defaux, 2007; Newsham *et al.*, 2009). Therefore, the adoption of a life cycle approach, where not only current energy concerns are accounted for but also long-term energy, environmental and social impacts should be adopted and integrated into design. Parallel to the development of sustainable buildings, the environmental impact of materials, products and new production processes throughout the life cycle of buildings with an analysis of LCA and life cycle cost analysis must be assessed. Additionally, materials that are not harmful to human health and that are recyclable are priorities for selection, which is in part within an LCA approach. Certification schemes such as C2C have material health as a primary material quality. Furthermore, for each developed product, the scenario at the end of its first life cycle should be determined and has a critical significance in the overall product LCA outcome. In the last few decades, thousands of studies with the aim to reduce the environmental impact of buildings have been performed, and it continues to be a very active development sector. At the same time, refined approaches for assessing a building's sustainability are under development (Haapio and Viitaniemi, 2008; Ding, 2008; Sinha and Kutnar, 2012).

Newly published standards for sustainability for construction works (CEN TC350) open opportunities for EU-wide harmonisation of calculations and reporting of a building's environmental impacts. The most important standards are EN 15804 for construction product EPDs and EN 15978 for assessment of environmental performance of new and existing construction works. In Mar. 2011, the CPR (305/2011) 2011 was introduced, replacing the CPD (89/106/EEC) 1993. The CPR came into full force in Jul. 2013. In order to develop a framework that allows for comparability of environmental performance between products, ISO 14025 (ISO (2006a)) was introduced. This describes the procedures required to produce Type III EPD. This is based on the principle of developing PCR, which specify how the information from an LCA is to be used to produce the EPD. For the construction sector, the core PCR is EN 15804 (CEN (2012b)). Currently, there are 28 EPD programmes referring to ISO 14025 (ISO (2006a)) that together provide 2256 PCR documents and more than 3600 EPDs (Passer *et al.*, 2015). Passer *et al.* (2015) performed a comprehensive comparison of national EPD programmes (Austria, Belgium, France, Germany and Switzerland) that are all based on EN 15804 (CEN (2012b)). The study concluded that the EPD programmes of listed countries are very similar and that harmonisation could only be reached by development of general guidelines and mutual recognition amongst different schemes. On the other hand, Lasvaux *et al.* (2015) compared two LCA databases, the Ecoinvent generic database and the EPD database developed in France. The databases were compared on three building LCA case studies: brick, reinforced concrete and timber frame structures. It was found that both databases can present very different values depending on the type of environmental indicator. For example, global warming potential has approximately 25% deviation amongst the databases, whilst photochemical ozone formation can vary amongst EPD and generic database with 100% or more. This indicates a lack of consistent metrics and guidance for practitioners, which presents a barrier to the widespread use of LCA in the European construction sector. In the European project EeBGuide, an online InfoHub was developed with the aim to provide guidance for LCA studies for energy-efficient buildings and present an interactive platform between research activities, standardisation activities and the practical implementation of LCA in the construction sector (Lasvaux *et al.*, 2014a). The platform is unfortunately not maintained, which is needed to assure widespread use of the InfoHub for LCA of construction works.

As sustainability becomes a dominant aspect of building development, the environmental impact of building materials should be included during planning with special attention paid to the life cycle and embodied energy of the materials used. Therefore, the LCA methodology should be used to reveal the environmental and energy performances of the used materials and the developed products through the whole life cycle. Since the 1980s, when the first LCA methodology was developed, till today, numerous methodologies to classify, characterise and normalise environmental effects have been developed. The most common, for example, CML 2 (2000), IPCC GHG emissions, Ecopoints 97 and Eco-indicator 99 (PRé Consultants, 2010), are focused on the following impact categories: acidification, eutrophication, ozone layer depletion, various types of ecotoxicity, photochemical ozone formation, resource depletion and global warming. As solutions are sought to reduce the impacts of buildings, LCA provides an objective measure for comparing building designs.

Building performance assessment can be very complex, as it must respond to multiple criteria, like energy consumption, acoustical performance, thermal occupant comfort, indoor air quality and many other issues. The functional unit has to be carefully defined. An assessment requires the use of predictive models that involve numerous design and physical parameters as their inputs (Hopfe *et al.*, 2013). Since these input parameters and the models that operate on them are not precisely known, it is imprudent to assume deterministic values for them. A more realistic approach is to introduce ranges of uncertainty in the parameters themselves or in their derivation, from underlying approximations.

Lasvaux *et al.* (2014b) delivered a list of future research needs in the field. They emphasised the development of dynamic LCA (taking into account spatial and temporal variations) for assessing the use phase of the building. It is suggested that parameters such as the degradation of performances of construction products and technical equipment and the precision of environmental data for energy processes for the electricity mix should be investigated. A further temporal dimension relates to the inherent uncertainties of end-of-life practices occurring in at least 50–100 years, for the buildings built today. In the absence of alternatives, current practices are most often assumed. Also, Passer *et al.* (2012) discussed the need for integrated LCAs that include the technical building equipment in evaluations of environmental performance of buildings. Hollberg and Ruth (2016) developed parametric model to try and address the need for design-integrated LCA and wider use of LCA in the building design process. The parametric model parameterises all input, including geometry, materials and boundary conditions, and generates LCA in real time. The simplified LCA can be used by architects to design solutions with minimum environmental impacts of new building or when designing the retrofitting of a single-family house.

Kuittinen *et al.* (2013) calculated the energy efficiency and carbon efficiency for eight wood-framed buildings from different European regions (Austria, Finland, Germany, Italy and Sweden). Using real buildings as an example, the study showed how the use of wood affects the carbon footprint and primary energy demand of buildings and concluded that country-specific data should be used in calculations.

Carre (2011) performed a cradle-to-grave LCA to compare environmental indicators of five different constructions of a typical single-storey Australian home with the same energy performance. Building materials, construction, operation, maintenance and end-of-life management phases were included. The results showed that global warming, photochemical oxidation formation, eutrophication, resource use and embodied energy are remarkably similar between the construction types. Land use, water use and solid waste indicators show more pronounced differences between construction types, with water and land use tending to be higher for timber-based construction types and solid waste tending to be higher in concrete slab designs. Variation between construction types is minimal for most indicators due to the dominance of the operational aspect of the building life cycle, which contributes 55%–86% of global warming impacts. Indicators such as land use, water use and solid waste are less affected by operation so it tends to be driven more by construction and end-of-life processes. Furthermore, a comparison of life cycle impacts excluding operation showed that timber-based construction tends to have lower global warming impacts than alternatives. In general, construction types incorporating timber tend to have lower global warming, resource use and embodied energy outcomes.

Robertson *et al.* (2012) quantified and compared the environmental impacts associated with alternative designs for a typical North American mid-rise office building. Two scenarios were considered: a traditional cast-in-place, reinforced concrete frame and a laminated timber hybrid design, which utilised engineered wood products (CLT and glulam). The results indicated that the laminated timber building design offered a lower environmental impact in 10 of 11 assessment categories.

The optimal design of buildings typically must account for multiple and competing objectives by simultaneously minimising energy consumption and environmental impact, without significantly increasing financial costs. Although meeting individual objectives by applying tailored strategies may be relatively simple, achieving the very high levels of performance is required to reduce energy use to nearly zero, whilst maintaining minimal costs is significantly more complex. This goal ideally requires applying the optimal combination of several strategies, which may be obtained through building energy simulations. However, simultaneously optimising a comprehensive set of passive solar design strategies quickly leads to design spaces that may be prohibitively large for available computational resources. Stevanović (2013) gave exhaustive review of the studies about simulation-based optimisation of passive solar design strategies. Although it is relatively simple to reduce the energy use up to some extent by applying individual strategies, very high levels of energy performance ideally require application of the optimal combination of several strategies, verified through building energy simulations, which are expected to be developed in the future. Furthermore, the service life information of a building plays an important role in life cycle studies, and therefore, not only technical factors influencing the lifetime of a building but also consumer behaviour should be considered. Aktas and Bilec (2012) studied the US residential building lifetime and its impact on LCA results. The study concluded that a product's actual lifetime was usually different than what the product was designed for and was determined by consumer behaviour.

Bio-based materials and construction products have a tremendous opportunity as we continue as society to strive for lower-impact buildings and construction works. The significance of the construction product sector on climate change through attributed emissions of carbon dioxide and other GHGs associated with material extraction, processing and product manufacture warrants a keen focus on lower environmental impact products. With the stored carbon in bio-based materials, we have a firm foundation to develop low-impact products for the future. Products that meet the need of users meet service life expectations and deliver wider benefits such as health and wellbeing to building occupants.

## References

Aktas, C.B., Bilec, M.M., 2012. Impact of lifetime on US residential building LCA results. Int. J. Life Cycle Assess. 17 (3), 337–349.

Allison, C., Carter, A., 2000. Study on Different Types of Environmental Labelling (ISO Type II and III Labels). Final Report for DG Environment. European Commission, Brussels, Belgium.

Ardente, F., Beccali, M., Cellura, M., Mistretta, M., 2008. Building energy performance: a LCA case study of kenaf-fibres insulation board. Energ. Buildings 40, 1–10.

Arena, U., Mastellone, M.L., Perugini, F., Clift, R., 2004. Environmental assessment of paper waste management options by means of LCA methodology. Ind. Eng. Chem. Res. 43, 5702–5714.

Beccali, M., Cellura, M., Fontana, M., Longo, S., Mistretta, M., 2013. Energy retrofit of a single-family house: life cycle net energy saving and environmental benefits. Renew. Sustain. Energy Rev. 27, 283–293.

Berndes, G., Ahlgren, S., Borjesson, P., Cowie, A., 2013. Bioenergy and land use change state of the art. WIREs Energy Environ. 2013 (2), 282–303.

Biswas, W., Graham, J., Kelly, K., John, M.B., 2010. Global warming contributions from wheat, sheep meat and wool production in Victoria, Australia—a life cycle assessment. J. Clean. Prod. 18, 1386–1392.

Blom, I., Itard, L., Meijer, A., 2010. Environmental impact of dwellings in use: maintenance of façade components. Build. Environ. 45, 2526–2538.

Blue Angel, 2013. Basic Criteria for Award of the Environmental Label, Low-Emission Floor Coverings. Panels and Doors for Interiors Made of Wood and Wood-Based Materials. Umweltbundesamt (Federal Environment Agency), Dessau-Roßlau, Germany. www.blauer-engel.de/en.

Börjesson, P., Gustavsson, L., 2000. Greenhouse gas balances in building construction: wood versus concrete from life-cycle and forest land-use perspectives. Energy Policy 28, 575–588.

Boulding, K.E., 1966. The economics of the coming spaceship earth. In: Jarrett, H. (Ed.), Environmental Quality in a Growing Economy: Essays From the Sixth RFF Forum. John Hopkins University Press, Baltimore, MD, pp. 3–14.

Brandão, M., Levasseur, A., Kirchbaum, M., Weidema, B., Cowie, A., Jorgensen, S., Hauschild, M., Pennington, D., Chomkhamsri, K., 2013. Key issues and options in accounting for carbon sequestration and temporary storage in life cycle assessment and carbon footprinting. Int. J. Life Cycle Assess. 18, 230–240.

Brander, M., 2015. Response to "Attributional life cycle assessment: is a land-use baseline necessary?"—appreciation, renouncement, and further discussion. Int. J. Life Cycle Assess. 20, 1607–1611.

Bribián, I.Z., Usón, A.A., Scarpellini, S., 2009. Life cycle assessment in buildings: state-of-the-art and simplified LCA methodology as a complement for building certification. Build. Environ. 44, 2510–2520.

Bribián, I.Z., Capilla, A.V., Usón, A.A., 2011. Life cycle assessment of building materials: comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. Build. Environ. 46, 1133–1140.

BSI, 2008. PAS2050 Specification for the Assessment of the Life Cycle Greenhouse Gas Emissions of Goods and Services. British Standards Institute, London, UK.

Buchanan, A., Levine, S., 1999. Wood-based building materials and atmospheric carbon emissions. Environ. Sci. Pol. 2, 427–437.

Cacho, O., Hean, R., Wise, R., 2003. Carbon-accounting methods and reforestation incentives. Aust. J. Agric. Resour. Econ. 47, 153–179.

Carre, A., 2011. A comparative life cycle assessment of alternative constructions of a typical Australian house design. Project report PNA147-0809. Forest and Wood Products Australia, Melbourne.

CEN, 2011. EN 15978:2011. Sustainability of construction works—assessment of environmental performance of buildings—calculation method. European Committee for Standardization, Brussels, Belgium.

CEN, 2012a. CEN/TC 350:2012. Sustainability of construction works. European Committee for Standardization, Brussels, Belgium.

CEN, 2012b. EN 15804:2012. Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products; German version EN 15804:2012+A1, 2013. European Committee for Standardization, Brussels, Belgium.

CEN, 2014a. EN 16449:2014. Wood and wood-based products—calculation of the biogenic carbon content of wood and conversion to carbon dioxide. European Committee for Standardization, Brussels, Belgium.

CEN, 2014b. EN 16485:2014. Round and sawn timber. Environmental product declarations. Product category rules for wood and wood-based products for use in construction. European Committee for Standardization, Brussels, Belgium.

Chaussinand, A., Scartezzini, J.L., Nik, V., 2015. Straw bale: a waste from agriculture, a new construction material for sustainable buildings. Energy Procedia 78, 297–302.

Cherubini, F., Guest, G., Strømman, A.H., 2013. Bioenergy from forestry and changes in atmospheric CO2: reconciling single stand and landscape level approaches. J. Environ. Manag. 129, 292–301.

CIRAIG, 2015. Circular economy: a critical literature review of concepts. International Reference Centre for the Life Cycle of Products, Processes and Services (October 2015). www.ciraig.org/pdf/CIRAIG_Circular_Economy_Literature_Review_Oct2015.pdf. (Accessed November 2016).

Citherlet, S., Defaux, T., 2007. Energy and environmental comparison of three variants of a single family house during its whole life span. Build. Environ. 42, 591–598.

CML2 baseline 2000 method, 2000. Centre of Environmental Science. Leiden University, NL. http://www.pre.nl/simapro/impact_assessment_methods.htm.

Construction Products Association, 2012. A Guide to Understanding the Embodied Impacts of ConstructionProducts.http://www.constructionproducts.org.uk/publications/sustainability/a-guide-to-understanding-the-embodied-impacts-of-construction-products/. (accessed November 2016).

Cuéllar-Franca, R.M., Azapagic, A., 2012. Environmental impacts of the UK residential sector: life cycle assessment of houses. Build. Environ. 54, 86–99.

De la Cruz, F.B., Chanton, J.P., Barlaz, M.A., 2013. Measurement of carbon storage in landfills from the biogenic carbon content of excavated waste samples. Waste Manag. 33, 2001–2005.

DHUP, 2013. French National Decree on the Environmental Declaration of All Construction Products. http://ftp.grenoble.cstb.fr/Public/Fouquet/Proceedings-Avnir/divers/Posters/Construction/251_Roy.pdf. (accessed November 2016).

Dias, A.C., Arroja, L., 2012. Environmental impacts of eucalypt and maritime pine wood production in Portugal. J. Clean. Prod. 37, 368–376.

Ding, C.K.C., 2008. Sustainable construction: the role of environmental assessment tools. J. Environ. Manag. 86, 451–464.

dos Santos, M.F.N., Battistelle, R.A.G., Bezerra, B.S., Varum, H.S.A., 2014. Comparative study of the life cycle assessment of particleboards made of residues from sugarcane bagasse (Saccharum spp.) and pine wood shavings (Pinus elliottii). J. Clean. Prod. 64, 345–355.

Ellen MacArthur Foundation, 2015. http://www.ellenmacarthurfoundation.org. (accessed March 2016).

European Commission, 2010. Commission decision on establishing the ecological criteria for the award of the Community Ecolabel for wooden floor coverings. Official Off. J. Eur. Union 2010/18/EC. http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32010D0018&from=EN.

European Commission, 2012. Innovating for Sustainable Growth—A Bioeconomy for Europe. European Commission, Brussels.

European Commission, 2016. Horizon 2020—The EU Framework Programme for Research and Innovation—Bioeconomy. http://ec.europa.eu/programmes/horizon2020/en/h2020-section/bioeconomy. (accessed March 2016).

Fahnestock, J., 2016a. The use of concept related to sustainable development in political and strategic documents. Deliverable 2.1 in the project European Global Transitional Network on Eco-Innovation, Green Economy and Sustainable Development. Innovation for Sustainable Development Network, Centre for European Economic Research (ZEW), Mannheim, Germany, 39 p.

Fahnestock, J., 2016b. Personal communication, March.

Fearnside, P., 2002. Why a 100-year time horizon should be used for global warming mitigation calculations. Mitig. Adapt. Strateg. Glob. Chang. 7, 19–30.

Ferreira J., Esteves B., Nunes L., Domingos I., 2016. Life cycle assessment of thermally treated and untreated maritime pine boards: a Portuguese case study. Int. Wood. Products J. 7 (3), 124–129.

Frischknecht, R., Althaus, H.-J., Bauer, C., Doka, G., Heck, T., Jungbluth, N., Kellenberger, D., Nemecek, T., 2007. The environmental relevance of capital goods in life cycle assessments of products and services. Int. J. Life Cycle Assess. 12, 7–17.

Ganne-Chédeville, C., Diederichs, S., 2015. Potential environmental benefits of ultralight particleboards with biobased foam cores. Int. J. Polym. Mater. 2015, 1–14.

González-García, S., Feijoo, G., Widsten, P., et al., 2009. Environmental performance assessment of hardboard manufacture. Int. J. Life Cycle Assess. 14, 456–466.

González-García, S., Dias, A.C., Arroja, L., 2013. Life-cycle assessment of typical Portuguese cork oak woodlands. Sci. Total Environ. 452–453, 355–364.

Gorse, C., Thomas, F., Glew, D., Miles Shenton, D., 2016. Achieving sustainability in new build and retrofit: building performance and life cycle analysis. In: Dastbaz, M., et al. (Eds.), Building Sustainable Futures. Springer International Publishing, Basel, http://dx.doi.org/10.1007/978-3-319-19348-9_8.

Gustavsson, L., Sathre, R., 2006. Variability in energy and carbon dioxide balances of wood and concrete building materials. Build. Environ. 41, 940–951.

Gustavsson, L., Joelsson, A., Sathre, R., 2010. Life cycle primary energy use and carbon emission of an eight-storey wood-framed apartment building. Energ. Buildings 42, 230–242.

Haapio, A., Viitaniemi, P., 2008. A critical review of building environmental assessment tools. Environ. Impact Assess. Rev. 28, 469–482.

Hardy, R.W.F., 2002. The bio-based economy. In: Janick, J., Whipkey, A. (Eds.), Trends in New Crops and New Uses. ASHS Press, Alexandria, VA, pp. 11–16.

He, Z., Zhang, Y., Wei, W., 2012. Formaldehyde and VOC emissions at different manufacturing stages of wood-based panels. Build. Environ. 47, 197–204.

Henry, B., 2012. Understanding the Environmental Impacts of Wool: A Review of Life Cycle Assessment Studies—A Report Prepared for Australian Wool Innovation & International Wool Textile Organisation. Agri Escondo Pty Ltd, IWTO, Brussels, Belgium, 58 p.

Hill, C.A.S., 2006. Wood Modification: Chemical, Thermal and Other Processes. John Wiley & Sons Ltd, Chichester, UK. ISBN: 978-0-470-02172-9. http://dx.doi.org/10.1002/0470021748.

Hill, C., Norton, A., 2014. The environmental impacts associated with wood modification balanced by the benefits of life extension. In: European Conference on Wood Modification 2014. pp. 8.

Hingston, J.A., Collins, C.D., Murphy, R.J., Lester, J.N., 2001. Leaching of chromated copper arsenate wood preservatives: a review. Environ. Pollut. 111, 53–66.

Hollberg, A., Ruth, J., 2016. LCA in architectural design—a parametric approach. Int. J. Life Cycle Assess. 21 (7), 943–960. http://dx.doi.org/10.1007/s11367-016-1065-1.

Hopfe, C.J., Augenbroe, G.A., Hensen, L.M., 2013. Multi-criteria decision making under uncertainty in building performance assessment. Build. Environ. 69, 81–90.

Ingrao, C., Bacenetti, J., Bezama, A., Blok, V., Geldermann, J., Goglio, P., et al., 2016. Agricultural and forest biomass for food, materials and energy: bio-economy as the cornerstone to cleaner production and more sustainable consumption patterns for accelerating the transition towards equitable, sustainable, post fossil-carbon societies. J. Clean. Prod. 117, 4–6.

IPCC, 2007. Climate change 2007: synthesis report. In: Pachauri, R.K., Reisinger, A. (Eds.), Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change Core Writing Team. IPCC, Geneva, Switzerland, 104 pp. www.ipcc.ch/report/ar4.

IPCC, 2013. Climate change 2013: the physical science basis. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., et al. (Eds.), Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, New York, NY. www.ipcc.ch/report/ar5/wg1.

IPCC, 2014. Climate change 2014: synthesis report. In: Core Writing Team, R.K., Pachauri, Meyer, L.A. (Eds.), Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland, 151 p. www.ipcc.ch/report/ar5/syr.

ISO, 2000. ISO 14020:2000. Environmental Labels and Declarations—General Principles. International Organization for Standardization, Geneva, Switzerland.

ISO, 2004. ISO 14024:2004. Environmental Labels and Declarations—Type 1 Environmental Labelling—Principles and Procedures. International Organization for Standardization, Geneva, Switzerland.

ISO, 2006a. ISO 14025:2006. Environmental Labels and Declarations—Type III Environmental Declarations—Principles and Procedures. International Organization for Standardization, Geneva, Switzerland.

ISO, 2006b. ISO 14040:2006. Environmental Management—Life Cycle Assessment—Principles and Framework. International Organization for Standardization, Geneva, Switzerland.

ISO, 2006c. ISO 14044:2006. Environmental Management—Life Cycle Assessment—Requirements and Guidelines. International Organization for Standardization, Geneva, Switzerland.

ISO, 2007. ISO 21930:2007. Sustainability in Building Construction—Environmental Declaration of Building Products. International Organization for Standardization, Geneva, Switzerland.

ISO, 2010. ISO 21931-1:2010. Sustainability in Building Construction—Framework for Methods of Assessment of the Environmental Performance of Construction Works—Part 1: Buildings. International Organization for Standardization, Geneva, Switzerland.

ISO, 2016. ISO 14021:2016. Environmental Labels and Declarations—Self-Declared Environmental Claims (Type II Environmental Labelling). International Organization for Standardization, Geneva, Switzerland.

Jones, A.K., Jones, D.L., Cross, P., 2014. The carbon footprint of lamb: sources of variation and opportunities for mitigation. Agric. Syst. 123, 97–107.

Kellenberger, D., Althaus, H.-J., 2009. Relevance of simplifications in LCA of building components. Build. Environ. 44, 818–825.

Kuittinen, M., Ludvig, A., Weiss, G., 2013. Wood in Carbon Efficient Construction; Tools, Methods and Application. CEI-Bois, Brussels, Belgium, 163 p.

Lasvaux, S., Gantner, J., Wittstock, B., Bazzana, M., Schiopu, N., Saunders, T., Gazulla, C., Mundy, J.A., Sjöström, C., Fullana-i-Palmer, P., Barrow-Williams, T., Braune, A., Anderson, J., Lenz, K., Takacs, Z., Hans, J., Chevalier, J., 2014a. Achieving consistency in life cycle assessment practice within the European construction sector: the role of the EeBGuide InfoHub. Int. J. Life Cycle Assess. 19, 1783–1793.

Lasvaux, S., Ventura, A., Habert, G., De La Roche, C., Hermel, K., Feraille, A., Tardivel, Y., Tessier, C., 2014b. Linking research activities and their implementation in practice in the construction sector: the LCA construction 2012 experience. Int. J. Life Cycle Assess. 19, 463–470.

Lasvaux, S., Habert, G., Peuportier, B., Chevalier, J., 2015. Comparison of generic and product-specific Life Cycle Assessment databases: application to construction materials used in building LCA studies. Int. J. Life Cycle Assess. 20, 1473–1490.

Levasseur, A., Lesage, P., Margni, M., Samson, R., 2013. Biogenic carbon and temporary storage addressed with dynamic life cycle assessment. J. Ind. Ecol. 17, 117–128.
Marland, E., Marland, G., 2003. The treatment of long-lived, carbon-containing products in inventories of carbon dioxide emissions to the atmosphere. Environ. Sci. Pol. 6, 139–152.
Marland, E., Stellar, K., Marland, G., 2010. A distributed approach to accounting for carbon in wood products. Mitig. Adapt. Strateg. Glob. Chang. 15, 71–91.
Menet, J.L., Gruescu, I.C., 2012. A comparative life cycle assessment of exterior walls constructed using natural insulation materials. Environ. Eng. Sust. Dev. Entrep. 1 (4), 14.
Moura-Costa, P.H., Wilson, C., 2000. An equivalence factor between CO2 avoided emissions and sequestration-description and applications in forestry. Mitig. Adapt. Strateg. Glob. Chang. 5, 51–60.
Murphy, R.J., Norton, A., 2008. Life cycle assessments of natural fibre insulation materials final report. In: 11th Int. Conf. Non-Conventional Mater Technol NOCMAT 2009. University of Bath, Bath, UK, 79.
Nabuurs, G.J., Pussinen, A., Karjalainen, T., Erhard, M., Kramer, K., 2002. Stemwood volume increment changes in European forests due to climate change-a simulation study with the EFISCEN model. Glob. Chang. Biol. 8, 304–316.
Nässén, J., Hedenus, F., Karlsson, S., Holmberg, J., 2012. Concrete vs. wood in buildings—an energy system approach. Build. Environ. 51, 361–369.
Newsham, G.R., Mancini, S., Birt, B.J., 2009. Do LEED-certified buildings save energy? Yes, but…. Energy Build. 41, 897–905.
NF, 2004. NF P01-010: 2004. Qualité environnementale des produits de construction - Déclaration environnementale et sanitaire des produits de construction. AFNOR, Paris, France. https://www.boutique.afnor.org/norme/nf-p01-010/qualite-environnementale-des-produits-de-construction-declaration-environnementale-et-sanitaire-des-produits-de-construction/article/663460/fa136284.
Norgate, T., Haque, N., 2010. Energy and greenhouse gas impacts of mining and mineral processing operations. J. Clean. Prod. 18, 266–274.
Ortiz, O., Pasqualino, J.C., Castells, F., 2010. The environmental impact of the construction phase: an application to composite walls from a life cycle perspective. Resour. Conserv. Recycl. 54, 832–840.
Pajchrowski, G., Noskowiak, A., Lewandowska, A., Strykowski, W., 2014. Wood as a building material in the light of environmental assessment of full life cycle of four buildings. Constr. Build. Mater. 52, 428–436.
Palumbo, M., 2015. Contribution to the development of new bio-based thermal insulation materials made from vegetal pith and natural binders (PhD thesis). Universitat Politècnica de Catalunya, 187 p.
Pargana, N., Pinheiro, M., Silvestre, J., Brito, J., 2014. Comparative environmental assessment of thermal materials of buildings. Energy Build. 82, 466–481.
Passer, A., Kreiner, H., Maydl, P., 2012. Assessment of the environmental performance of buildings: a critical evaluation of the influence of technical building equipment on residential buildings. Int. J. Life Cycle Assess. 17, 1116–1130.
Passer, A., Lasvaux, S., Allacker, K., De Lathauwer, D., Spirinckx, C., Wittstock, B., Kellenberger, D., Gschösser, F., Wall, J., Wallbaum, H., 2015. Environmental product declarations entering the building sector: critical reflections based on 5 to 10 years experience in different European countries. Int. J. Life Cycle Assess. 20, 1199–1212.
Pearce, D.W., Turner, R.K., 1989. Economics of Natural Resources and the Environment. Johns Hopkins University Press, Baltimore, MD.

Penaloza, D., Sandin, G., Røyne, F., 2016. The influence of system boundaries and baseline in climate impact assessment of forest products. J. Clean. Prod. 116, 90–99.
Pilli, R., Fiorese, G., Grassi, G., 2015. EU mitigation potential of harvested wood products. Carbon Balance Manage. 10, 6.
Pizzi, A., 2008. Tannins: major sources, properties and applications. In: Naceur Belgacem, M., Gandini, A. (Eds.), Monomers, Polymers and Composites from Renewable Resources. Elsevier, London, UK, pp. 179–199. ISBN: 978-0-08-045316-3.
PRé Consultants, 2010. Impact Assessment Methods. http://www.pre.nl/simapro/impact_assessment_methods.htm#EP97. (accessed 01.04.16).
Rivela, B., Hospido, A., Moreira, T., Feijoo, G., 2005. Life cycle inventory of particleboard: a case study in the wood sector. Int. J. Life Cycle Assess. 11, 106–113.
Robertson, G.P., Collins, S.L., Foster, D.R., Brokaw, N., Ducklow, H.W., Gragson, T.L., Gries, C., Hamilton, S.K., McGuire, A.D., Moore, J.C., Stanley, E.H., Waide, R.B., Williams, M.W., 2012. Long-term ecological research in a human-dominated world. Bioscience 62, 342–353.
Roffael, E., 2006. Volatile organic compounds and formaldehyde in nature, wood and wood based panels. Holz Roh Werkst. 64, 144–149.
Roodman, D.M., Lenssen, N., 1995. A building revolution: how ecology and health concerns are transforming construction. Worldwatch Paper #124, ISBN: 1-878071-25-4.
Røyne, F., Peñaloza, D., Sandin, G., Berlin, J., Svanström, M., 2016. Climate impact assessment in life cycle assessments of forest products: implications of method choice for results and decision-making. J. Clean. Prod. 116, 90–99.
Salazar, J., Meil, J., 2009. Prospects for carbon-neutral housing: the influence of greater wood use on the carbon footprint of a single-family residence. J. Clean. Prod. 17 (17), 1563–1571.
Sandin, G., Peters, G.M., Svanström, M., 2014. Life cycle assessment of construction materials: the influence of assumptions in end-of-life modelling. Int. J. Life Cycle Assess. 19 (4), 723–731.
Sathre, R., González-García, S., 2014. Life cycle assessment (LCA) of wood-based building materials. In: Pacheco-Torgal, F., Cabeza, L.F., Labrincha, J., de Magalhaes, A.G. (Eds.), Eco-Efficient Construction and Building Materials. Woodhead Publishing (Elsevier), London, UK, pp. 311–337.
Sathre, R., Gustavsson, L., 2009. Using wood products to mitigate climate change: external costs and structural change. Appl. Energy 86, 251–257.
Scarlat, N., Dallemand, J.-F., Monforti-Ferrario, F., Nita, V., 2015. The role of biomass and bioenergy in a future bioeconomy: policies and facts. Environ. Dev. 16, 3–34.
Schmidt, A.C., Jensen, A.A., Clausen, A.U., et al., 2004. A comparative life cycle assessment of building insulation products made of stone wool, paper wool and flax. Int. J. Life Cycle Assess. 9, 122–129.
Shirley, K., Marland, E., Cantrell, J., Marland, G., 2011. Managing the cost of emissions for durable, carbon-containing products. Mitig. Adapt. Strateg. Glob. Chang. 16, 325–346.
Sierra-Pérez, J., Boschmonart-Rives, J., Dias, A.C., Gabarrell, X., 2016. Environmental implications of the use of agglomerated cork as thermal insulation in buildings. J. Clean. Prod. 126, 97–107.
Silva, D.A.L., Lahr, F.A.R., Garcia, R.P., Freire, F.M.C.S., Ometto, A.R., 2013. Life cycle assessment of medium density particleboard (MDP) produced in Brazil. Int. J. Life Cycle Assess. 18, 1404–1411.
Silva, D.A.L., Lahr, F.A.R., Pavan, A.L.R., et al., 2014. Do wood-based panels made with agro-industrial residues provide environmentally benign alternatives? An LCA case study of sugarcane bagasse addition to particle board manufacturing. Int. J. Life Cycle Assess. 19 (10), 1767–1778.

Sinha, A., Knowles, C., 2014. Green building and the global forest sector. In: Hansen, E., Panwar, R., Vlosky, R. (Eds.), The Global Forest Sector: Changes, Practices, and Prospects. CRC Press, Boca Raton, FL; London; New York, NY, pp. 261–280.

Sinha, A., Kutnar, A., 2012. Carbon footprint versus performance of aluminum, plastic, and wood window frames from cradle to gate. Buildings 2, 542–553.

Soimakallio, S., Cowie, A., Brandão, M., Finnveden, G., Ekvall, T., Erlandsson, M., Koponen, P., Karlsson, P.-E., 2015. Attributional life cycle assessment: is a land-use baseline necessary? Int. J. Life Cycle Assess. 20, 1364–1375.

SPF Santé Publique, 2015. Health, food chain safety and environment. The Belgian Framework for Environment Messages Concerning Construction Products and Environmental Product Declarations (EPD). Federal Public Service (FPS) Health, Food Chain Safety and Environment, Brussels, Belgium. www.health.belgium.be/fr/le-cadre-belge-pour-les-messages-environnementaux-sur-les-produits-pour-la-construction-et-les#Document. (accessed November 2016).

Stahel, W.R., Reday-Mulvey, G., 1981. Jobs for Tomorrow, the Potential for Substituting Manpower for Energy. Vantage Press, New York, NY.

Stevanović, S., 2013. Optimization of passive solar design strategies: a review. Renew. Sustain. Energy Rev. 25, 177–196.

van Dam, J.E.G., Bos, H.L., 2004. The Environmental Impact of Fibre Crops in Industrial Applications. Food and Agriculture Organization, Rome.

van der Lugt, P., van den Dobbelsteen, A.A.J.F., Janssen, J.J.A., 2006. An environmental, economic and practical assessment of bamboo as a building material for supporting structures. Constr. Build. Mater. 20, 648–656.

VINNOVA, 2013. A Bio-Based Economy—A Strategic Research and Innovation Agenda for New Businesses. http://www.vinnova.se/PageFiles/751324632/A%20BIO-based%20Economy.pdf. (accessed March 2016).

Werner, F., Richter, K., 2007. Wood building products in comparative LCA: a literature review. Int. J. Life Cycle Assess. 12 (7), 470–479.

Wilson, J.B., 2009. Life-cycle inventory of particleboard in terms of resources, emissions, energy and carbon. Wood Fiber Sci. 42, 90–106.

Wolf, M.-A., Pant, R., Chomkhamsri, K., Sala, S., Pennington, D., 2012. International Reference Life Cycle Database (ILCD) Handbook—Towards More Sustainable Consumption and Production for a Resource Efficient Europe. Joint Research Centre, Luxembourg Publications Office of the European Union, Luxembourg.

Yuan, Z., Bi, J., Morgiguchi, Y., 2008. The circular economy: a new development strategy in China. J. Ind. Ecol. 10 (1–2), 4–8.

Zhijun, F., Nailing, Y., 2007. Putting circular economy into practice in China. Sustain. Sci. 2, 95–101.