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The Environmental Impact of Industrial Bamboo Products:

Life-cycle Assessment and Carbon Sequestration

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INBAR

The International Network for Bamboo and Rattan (INBAR) is an intergovernmental organization with member countries all over the world dedicated to improving the well-being of the producers and users of bamboo and rattan within the context of a sustainable bamboo and rattan resource base. INBAR plays a unique role in finding and demonstrating innovative ways of using bamboo and rattan to protect the environment and biodiversity, alleviate poverty and facilitate fairer pro-poor trade. INBAR connects a global network of partners from the government, private and non-profit sectors to define and implement a global agenda for sustainable development through bamboo and rattan. For more information, please visit www.inbar.int.

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Foreword

Dr. Hans Friederich
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Our continuously changing consumption patterns are applying increasing pressure on the world's global resources, which is visible through the various financial, food and climate crises around the globe. This calls for a more sustainable and green approach to economic development, from the source of the raw materials to the disposal of the waste after consumption. At the supply side, the use of sustainably produced materials from sources such as fast-growing bamboo can help to offset the negative effects of other production chains, provided the bamboo is harvested from a natural forest or a plantation that was created to improve degraded lands.

The Life-cycle Assessment concept is used in this study to assess the environmental impact, including carbon footprint of industrial products in Western Europe made from bamboo, and to compare this with more commonly used materials such as tropical hardwood. This INBAR technical report is an updated version of the environmental assessments made in the PhD thesis "Design Interventions for Stimulating Bamboo Commercialization" by Pablo van der Lugt (2008). The data used in this new study are based on the latest production figures in the bamboo production chain and updates of relevant databases.

The report is targeted towards any stakeholder in the bamboo or wood production chain that wants to get a better understanding of the environmental and climate change impacts of bamboo materials used for construction compared to wood and other alternatives. The Life-Cycle Assessment also provides insight into the impact of each step in the production process on the overall environmental impact of the material. As a result of the assessment, the supplier of the bamboo materials used in this study, MOSO International BV, has been able to improve the production process of several of its bamboo materials.

Our hope is that this scenario may be relevant for other industrial bamboo manufacturers who want to lessen the environmental impacts of their products. The report also aims to further capture and highlight the environmental potential of bamboo, and to ultimately increase its global market share given the growing focus on sustainable building worldwide.

The authors have assumed that the bamboo raw material which is sourced from Central China, originates from either natural bamboo stands, or from plantations that have been established in response to the recent landscape improvement programmes of the central government. This programme aims to transform slope agriculture and barren lands into healthy, productive forest land, and does not include the clearing of natural forests or peat lands to plant bamboo. The assessments provided in this report would not be correct if the planting of bamboo had caused destruction of natural habitats.We hope that with the production of this report, INBAR has contributed to the discussion about the positive role that bamboo can play in mitigating climate change effects, and in helping people to adapt to the impact of climate change on their surroundings.

Executive summary

This report gives a Life-Cycle Assessment (LCA) and carbon footprint analysis on a selection of industrial bamboo products.

The LCA is made for cradle-to-gate, plus the end-of-life stages of the bamboo products. For end-of-life it is assumed that 90% of the bamboo products are incinerated in an electrical power plant, and 10% will end-up in landfill, which is considered to be a realistic scenario for the Netherlands (NEN 8006) and Western Europe.

In addition to the standard LCA (ISO 14040 and 14044), the sequestration (capture and storage) of CO2 has been taken into account. The report provides a comprehensive explanation how such a calculation on carbon sequestration must be made within the general logic of the LCA methodology (and the general logic in science), since there is a lot of confusion regarding this issue.

This LCA has been performed for the specific production chain of industrial bamboo products of the company MOSO International BV following best practice and can therefore not be perceived as being typical for the production chain of other industrial bamboo material manufacturers.

The overall result of the calculations is that, if production parameters are optimised, industrial bamboo products can have a negative carbon footprint over their full life cycle (from cradle till grave), i.e. the credits through carbon sequestration and energy production in the end-of-life phase in an electrical power plant outweigh the emissions caused by production and transport.

Glossary

Biogenic CO2 relates to CO2 which is captured in biomass during the growth of a plant or tree and consequently in a biologically based product.

Carbon footprint is a commonly used methodology in which the greenhouse gas emissions during the life cycle of a product can be measured in terms of kg CO2 equivalent (CO2e).

Carbon negative relates to a negative outcome of a carbon footprint of a product i.e. carbon credits through carbon sequestration and energy production in the end of life phase are higher than the emissions caused by production and transport.

Carbon sequestration is the process of capture and storage of atmospheric carbon dioxide, in this case in bamboo biomass (forests and products).

Cradle-to-gate relates to the aggregated environmental impact of a product from resource extraction, transport and final processing until ready for shipment to the final customer at the factory gate.

Cradle-to-grave - besides the impact in the cradle to gate (production) phase, a cradle to grave assessment also includes the aggregated environmental impact of a product during the use and end-of-life phase, thus over the full life cycle.

Eco-costs is a single indicator in LCA (see below) used to express the total amount of environmental burden of a product over its lifecycle in one number, on the basis of prevention of that burden.

Life-Cycle Assessment (LCA) is a methodology used to assess the environmental impact associated with all stages of a products life cycle from-cradle-to-grave (see above). In contrast to a carbon footprint assessment, LCA is based on several environmental indicators which besides the Global Warming Potential (carbon footprint) also includes acidification, euthrophication, smog, dust, toxicity, depletion, land-use and waste.

Life-Cycle Inventory (LCI) is a phase in LCA in which an inventory of flows of a product system is developed including inputs of water, energy, and raw materials, and releases to air, land, and water.

1 | Aim of the study

There were two reasons for carrying out this Life-Cycle Assessment (LCA):

a) to establish the strengths and weaknesses of industrial bamboo products and the production process in terms of CO_2 and toxic emissions in order to further improve the sustainability of these products, and
b) to determine the environmental impact and carbon footprints of industrial bamboo products throughout their lives.

The analyses in this report are fully in line with the ISO specifications (ISO 14040 and 14044) and the LCA manual for LCA (EC-JRC 2010). Details on the calculations have been published in peer reviewed papers (Vogtländer et al. 2014, Vogtländer et al. 2010) and books (van der Lugt et al. 2009a, van der Lugt et al. 2009b, van der Lugt 2008). Therefore, an extra critical review of this report (as normally required in LCA studies which are intended to be disclosed to the public) has been regarded as superfluous.

There is a distinction of two levels of carbon sequestration, i.e., storage of CO_2 in natural renewable products (like wood, bamboo and agricultural products):

1. the level of the life cycle of a product (from cradle-to-grave), which is the domain of LCA analyses
2. the level of the global CO_2 cycles and global storage of CO_2, which is not the domain of a standard LCA, and which has to be analysed separately.

Discussions on carbon sequestration are often blurred, since the aforementioned distinction in system levels are often not made clear. This leads to a secondary goal of this report:

- to clarify the LCA calculation as such, and the way "biogenic CO_2" (CO_2 which is captured in biomass) is dealt with in the life cycle
- to clarify how carbon sequestration on a global scale can be defined and calculated for bamboo products, and can be incorporated into the standard LCA calculations.

The analyses on biogenic CO_2 in LCA and carbon sequestration on a global scale are according to recent publications on this subject (Vogtländer et al. 2014, Vogtländer 2010).

Scope | 2

The scope of this LCA study is based on the product portfolio of MOSO International BV:

- flooring & floor covering (solid strip, solid wide board, 2-ply flooring, industrial flooring)
- thermally modified decking and cladding
- panels & beams (solid panel, 1-ply panel, veneer, solid joist)

Excluded from the scope are engineered bamboo flooring products e.g. bamboo toplayer on a HDF / MDF carrier.

The system boundary of this LCA is “cradle-to-warehouse-gate” plus “end-of-life” as depicted in Fig. 1. The use-phase has been kept out of the analyses, because the emissions in this step are negligible (in comparison to the first and the last step) and often based on user preferences (e.g. application of oil on a floor or leaving it untreated).

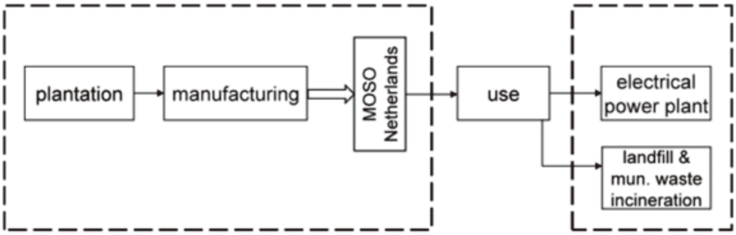


Figure 1: System boundary: cradle-to-gate plus end-of-life.

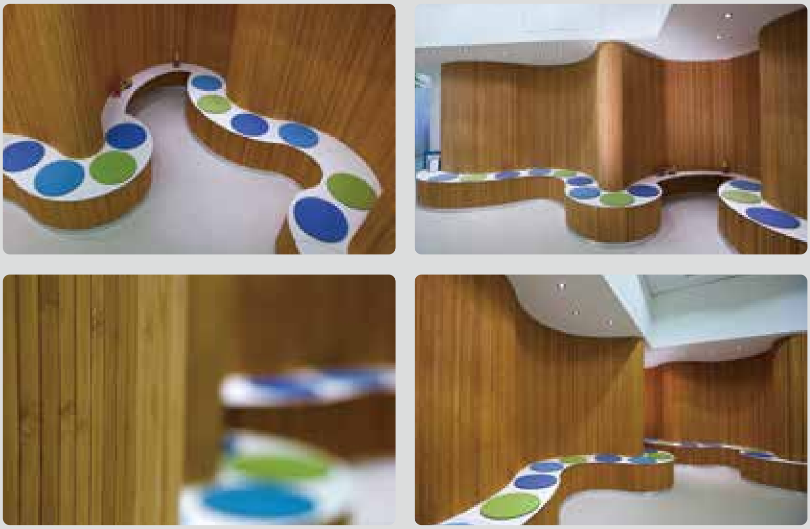
Note: This LCA has been performed for the specific production chain of industrial bamboo products of MOSO International BV following best practice and can therefore not be perceived as being typical for the production chain of other industrial bamboo material manufacturers.

The final analysis is not done at the level of so called "midpoints" (environmental impact indicators for specific environmental themes such as toxicity, acidification, etc) since a set of midpoints is not meaningful for the average reader (even specialists often struggle with a meaningful interpretation of midpoints). In this report, so called "single indicators" are used. The advantage of a single indicator is that the combined environmental impact of all environmental categories of the product's life cycle is expressed in one number.

Two single indicators are used:

- the "CO2 equivalent" (carbon footprint) , which can easily be understood and explained, but is lacking other polluting emissions (like SOx, NOx, carcinogens, fine dust, and so on).
- the "eco-costs" system which incorporates 3000 polluting substances (as well as materials depletion), see Annex I.

An important advantage of bamboo is its yield of land due to the high growing speed. This additional sustainability issue, typically excluded in LCA, is dealt with in Annex II. Some social aspects of the manufacturing of bamboo products are dealt with in Annex II.



Scientific background of LCA and the CO2 cycle | 3

Note: the text in this chapter is largely a quotation of section 4 of Vogtländer et al. (2014)

Sequestration (the capture and storage) of CO2 in wood is an important issue in sustainability. However, it is also a confusing subject, leading to many discussions. This chapter provides a summary of this complex issue, which is related to the “delayed pulse” issue and the issue of “system expansion” in LCA. For a scientific analysis see Vogtländer at al. (2014).

<u>Carbon sequestration in LCA on the level of a product.</u>
There is consensus in science on the way “biogenic CO2” (CO2 which is captured in wood / bamboo during the growth of a tree / stem) is to be handled in LCA. See Fig.2.

Biogenic CO2 is first taken out of the air at the bamboo plantation, and then released back to the atmosphere at the end-of-life stage. So biogenic CO2 is recycled, and its net effect on global warming is zero.

However, when the bamboo product is burnt at end-of-life in an electrical power plant, the total system of Fig. 2 generates electricity. This electricity can replace electricity from fossil fuels. In other words: the use of fossil fuels is avoided, so fossil CO2 emissions are avoided, which results in a reduction of global warming. In LCI calculations this leads to a system credit: the production of heat or electricity from bamboo waste has a negative carbon footprint and negative eco-costs. This is the so-called substitution approach in consequential modelling, see Section 14.5 of the ILCD Handbook (ECJRC 2010).

The conclusion is that the storage of biogenic CO2 (carbon sequestration) in bamboo is not counted in LCA, unless the bamboo (or any other bio-product like wood) is burnt for electricity or heat. A better efficiency of the production of electricity results in a higher credit.

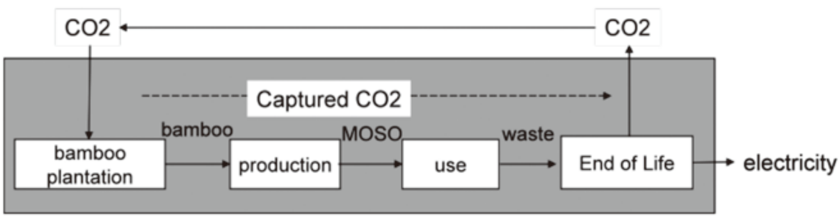


Figure 2: The CO2 cycle on product level.

The widespread confusion comes from the fact that the storage of CO_2 as such, even temporary, is good for the environment, so “it has to be incorporated in some way in the total LCA calculation”. However, the positive effect of storage cannot be analysed on the level of one single product, although this attempt has been made by two important LCA systems, through provision of a credit for temporary storage of carbon in bio-based renewable products: the ILCD Handbook (EC-JRC 2010) and the PAS 2050:2011 Specification (BSI 2011).

However, this ‘optional’ method in the ILCD manual and PAS 2050:2011 (i.e., through the discounting of delayed CO_2 emissions) results in an overestimation of the benefits of temporary fixation of biogenic CO_2. This optional method does not fulfil the precautionary principle, and should therefore be avoided in LCA (Vogtländer et al. 2014).

Therefore, compared to the temporary storage credit specified as “optional” in PAS 2050 and the ILCD manual, this report adopts an alternative, more realistic approach on how to cope with carbon sequestration in renewable products, which will be explained below.

The effects of carbon sequestration at global system level

On a global scale, CO_2 is stored in forests (and other vegetation), in the ocean, and in products (e.g. buildings and furniture). The details of carbon mass balances are very complex; however, an understanding of the basics of the proposed LCA allocation method in this report requires a system approach which starts from the highest possible aggregation level (the so-called “Tier 1” and “Tier 2” approach of the Intergovernmental Panel on Climate Change - IPCC). In this approach we look at vast forest areas (e.g. Scandinavia, the Baltic countries, European Russia, Siberia, Canada, New Zealand). At this aggregation level there is a continuous rotation of the forests. The local time dependent carbon sequestration effects caused by harvesting are levelled out within the region, since only a small proportion of the trees are harvested each year.

Fig. 3 is a simplified schematic overview of the highest aggregation level of the global carbon cycle.

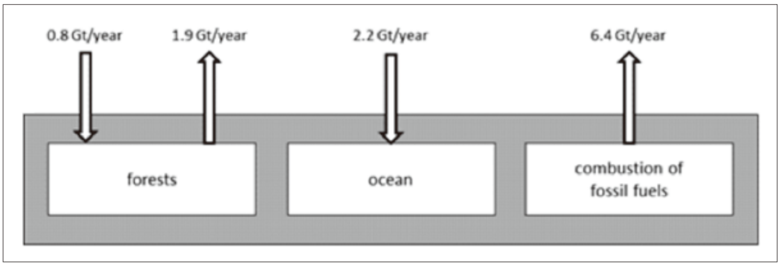


Figure 3: Global anthropogenic fluxes of CO_2 (Gt/year) over the period 2000–2010

The issue is that the anthropogenic CO_2 emissions on a global scale can be characterised by three main flows:

- carbon emissions per year caused by burning of fossil fuels: 6,4 Gt/year (Solomon et al. 2007)
- carbon emissions per year caused by deforestation in tropical and sub-tropical areas (Africa, Central America, South America, South and Southeast Asia): 1,93 Gt/year (FAO 2010)
- carbon sequestration per year by re-growth of forests on the Northern Hemisphere (Europe, North America, China): 0,85 Gt/year (FAO 2010).

It can be concluded that the global carbon cycle can significantly be improved in the short term by the following changes: 1. burn less fossil fuels, 2. stop deforestation, 3. intensify the use of forests on the Northern Hemisphere by better management and wood production in plantations, 4. afforestation (plant trees on soils that have not supported forests in the recent past), 5. increase application of wood in durable (construction) products in buildings.

However, it is far too simple to claim that application of wood in design and construction will lead to carbon sequestration, and therefore it will counteract global warming. It depends on the origin of wood and the growth of the wood markets. One should realise that, if there is no change in the area of forests and no change in the volume of wood in buildings, there is no change in sequestered carbon on a global level and hence no effect on carbon emissions. This means that only when more carbon is being stored in forests (either by area expansion with an increase of net carbon storage on that land, or by increased productivity in existing forests by improved management), and when the total volume of wood in buildings is increasing, there will be extra carbon sequestration.

In boreal and temperate regions such as in Europe and North America, the forest area has been increasing steadily for several decades due to afforestation and reforestation (see Fig. 4), which results in increased carbon storage over the last decennia (see Fig. 5).

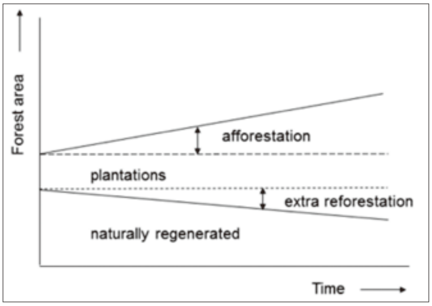


Figure 4: Higher demand of boreal and temperate softwood from Europe and North America leads to more carbon sequestration because of afforestation (extra forests) and reforestation (converting naturally regenerated forests to plantations and better forest management).

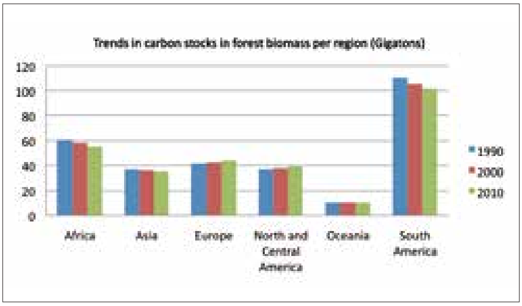


Figure 5: Trends in carbon storage in forests from 1990–2010 (Source: FAO 2010)

Fig. 5 also shows that carbon storage in tropical areas is decreasing. The demand for tropical hardwood is higher than the supply from plantations (only 35 - 40% of FSC-wood is from plantations). This leads to deforestation, resulting in carbon emissions caused by less carbon sequestration. This mechanism is depicted in Fig. 6.

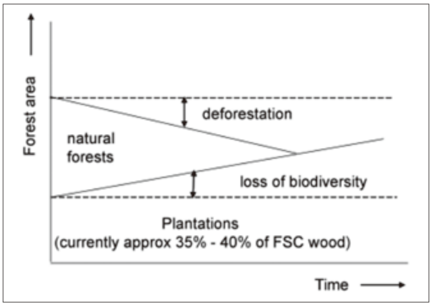


Figure 6: Higher demand of tropical hardwood leads to deforestation and less carbon sequestration

The conclusion in regard to the production side of wood is:

- extra demand of boreal and temperate softwood from Europe and North America leads to a better forest management and an increase in forest area, so more sequestered carbon (Fig. 4).
- (extra) demand of tropical hardwood leads to a decrease in forest area, so less sequestered carbon (Fig. 6).

Translating this to the case for bamboo provides the following conclusion:

- extra demand of bamboo from China has an effect on carbon sequestration which is similar to that of European and North American wood: it leads to a better forest management and an increase in bamboo forest area (Lou Yiping et al. 2010).

The carbon sequestration in wood in houses and offices is slowly rising on a global scale (because of increasing population), which is positive in terms of extra carbon sequestration. This volume of carbon sequestration, however, is low in comparison with the volume of standing trees in the forests: less than 30% of the carbon above the ground (less than 24% of the carbon above plus under the ground) ends up in housing (see Section 5, step 1 and step 4 in Vogtländer et al (2014)) and for bamboo this difference is even greater, see also chapter 6 of this report.

The conclusion is that carbon sequestration is enhanced when more boreal or temperate softwood from Europe and North America and/or bamboo is applied in buildings, since more carbon is sequestered in the forests as well as in buildings.

The consequence for bamboo is that there is only extra carbon storage on a global scale when there is market growth of the application of bamboo. This market growth leads to more plantations and more volume of bamboo in the building industry. In chapter 6 it is explained that the positive major effect on global warming is mainly caused by the increase of bamboo plantations, rather than by the increase of bamboo products (e.g., bamboo in buildings).

On the contrary, the application of tropical hardwood is damaging global carbon sequestration, since the decrease of carbon in the tropical forests is more than the increase of carbon in the wood products.

Figure 7: Bamboo is increasingly adopted by Western architects as building material, for example the international airport in Madrid by Richard Rogers (Photo MOSO International BV).

Another key issue of the global mass balance is that carbon sequestration is not increasing per house which is built, but per extra house that is built above the number of houses that are required to replace discarded, old, houses. This is an important consequence of the global mass balance, which is often overlooked by LCA practitioners when they study carbon sequestration at product level in the LCI (Life Cycle Inventory, i.e., analysis of all input and output flows in the product system) phase of the assessment.

This report adopts the more realistic allocation method which is presented in Vogtländer et al. (2014), based on the *extra global carbon sequestration in forests / plantations related to the total global production of wood / bamboo products*, which is explained in detail in chapter 6.

4 Cradle-to-gate calculations on bamboo products

The production system of bamboo "from cradle-to-warehouse-gate" is depicted in Fig. 8.

The calculations have been made on the actual product chain of bamboo products of the company MOSO International BV based on consumption in the Netherlands:

- Collection production data: October 2013 – January 2014
- Type of bamboo: Phyllostachys Pubescens (density 700 kg/m3, length up to 15 m, diameter on the ground 10-12 cm, wall thickness 9mm), also called "Moso bamboo" by the native population.
- Plantation and first processing: the Anji region, Zhejiang province, China
- Final processing in Hangzhou, Zhejiang province, and Jianyang, Nanping county, Fujian province, both in China
- The product is shipped via Shanghai and Rotterdam to the warehouse of MOSO International BV in the Netherlands (Zwaag)

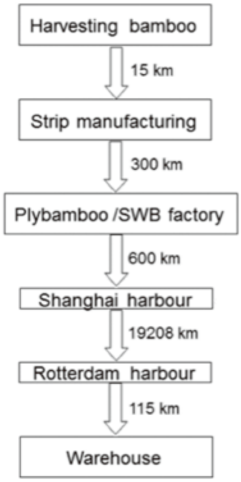


Figure 8: The production system of bamboo products of MOSO International BV (cradle-to-warehouse-gate).

The required heat for the manufacturing process is generated locally by combustion of sawdust and bamboo waste produced during the manufacturing process.

Electricity is from the local grid.

Note: a cogeneration plant for electricity and heat is an opportunity for the future to reduce the carbon footprint even further.

The calculations for the LCAs have been made with the computer program Simapro version 8.01, applying LCI databases of Ecoinvent v3 (2014) and Idemat 2014 (a database of the Delft University of Technology, partly based on Ecoinvent Unit data). The eco-costs of construction materials (from cradle to gate) and transport can be found in the open access tables provided at www.ecocostsvalue.com or can be calculated with the Idemat databases for Simapro.

In general, there are three main production techniques used for the development of industrial bamboo products:

- lamination of strips (700 kg/m^3)
- compression of rough strips / fibers (1100-1200kg/m^3)
- flattened bamboo (850 kg/m^3)

Based on these three main production techniques the eco-costs of various derived products can be calculated, for example a 1ply Plybamboo panel or 5 ply Plybamboo panel are produced in a similar way and per kilogram product will only have slightly lower (1 ply, less resin content, less pressing) or slightly higher (5ply, more resin, more pressing) eco-costs.
Below these main production technologies are further explained and the LCI is provided for each main technology.

A more comprehensive description of the production processes and tables for the other varieties can be found in van der Lugt (2008) and van der Lugt et al. (2009a, 2009b). The total scores (carbon footprint as well as eco-costs) of the various variations for the industrial bamboo products are given in Chapter 7.

Lamination of strips (plybamboo)

The lamination of fine, straight, strips to develop panels, beams and flooring boards is the most commonly used technology to develop industrial bamboo products. Depending on the positioning of the strips in the toplayer the style is called “plain pressed” (flat strips) or “side pressed” (strips on side). Furthermore, the input strips can either be bleached (‘natural’ colour), carbonized (‘caramel’ colour) or double carbonized (‘chocolate’ colour) to acquire a different colour. This type of bamboo product is also referred to as “plybamboo”.

The basic length of the bamboo strips is 2,66 meters, based on which the complete Chinese industrial bamboo industry is standardised. Usually about 8 meters (3 x 2,66 m) of a harvested bamboo stem will be used for the development of bamboo products. The bottom two parts of the 2,66 meters are mostly used as input for the manufacturing of industrial bamboo materials such as laminated bamboo boards, while the upper part may be used for smaller bamboo products such as blinds and chopsticks.

The bottom segments of the stem will first be processed into rough strips (approximately 2630 x 23 x 8mm). This is done near the plantations. The strips are then transported to the manufacturing site of the laminated bamboo board, see Fig. 8. In the case of MOSO International BV, the distance to the manufacturing site of laminated bamboo board was 300 km.

Figure 9: Plybamboo boards are available in various colours, sizes and styles; in the plain pressed style, the nodes are clearly visible (see two pictures on the left). In the side pressed version, they are less visible (two pictures on the right). Photos: MOSO International BV

Description of process step	amount	unit	CO2equ/FU	CO2equ/kg	percentage
1. Cultivation and harvesting from plantation					
Gasoline consumption	0,224	liter / FU	0,651	0,0156	1,5%
2. Transport from plantation to strip manufacturing facility					
Eco-costs of a 5 tons truck (EURO 3, transport of 23.1 FUs)	30	km / truck	0,699	0,0168	1,6%
3. Strip making	1,38	kWh/ FU	0,797	0,0191	1,9%
4. Transport from strip manufacturing facility to factory					
Eco-costs (28 tons truck EURO3, 300km)	12,51	ton.km / FU	2,314	0,0555	5,5%
5. Rough planing	8,62	kWh/ FU	4,977	0,1193	11,7%
6. Strip selection					
7. Carbonization	4,73	kWh/FU	2,731	0,0655	6,4%
8. Drying carbonized strips	9,66	kWh/FU	5,577	0,1337	13,1%
9. Fine planing	5,8	kWh/FU	3,349	0,0803	7,9%
10. Glue application (1-layer boards)					
Added amount of Melamine formaldehyde (dry condition)	0,483	kg / FU	1,657	0,0397	3,9%
11. Pressing strips to 1- layer board	1,89	kWh/FU	1,091	0,0262	2,6%
12. Sanding 1- layer board	1,62	kWh/FU	0,935	0,0224	2,2%
13. Glue application (3-layer board)					
Added amount Emulsion Poly Isocyanate (dry condition)	0,908	kg / FU	1,476	0,0354	3,5%
14. Pressing three layers to one board	1,65	kWh/FU	0,953	0,0228	2,2%
15. Sawing	0,29	kWh/FU	0,167	0,0040	0,4%
16. Sanding 3-layer board	0,86	kWh/FU	0,497	0,0119	1,2%
17. Dust absorption (during all steps)	8,67	kWh/FU	5,005	0,1200	11,8%
18. Transport from factory to harbour					
Eco-costs (28 tons truck EURO3, 300km)	12,51	ton.km / FU	2,314	0,0555	5,5%
19. Transport from harbour to harbour					
Eco-costs (20ft container in a transoceanic freight ship, 19208 km)	801	ton.km / FU	6,456	0,1548	15,2%
20. Transport from harbour to warehouse					
Eco-costs (28 tons truck EURO5, 115km)	4,80	ton.km / FU	0,806	0,0193	1,9%
TOTAL carbonized			42,45	1,018	100,0%

Table 1: Input data and results in CO2 equivalent (carbon footprint, cradle-to-gate) of carbonized 3-layer laminated bamboo board (consisting of two layers of 5 mm plain pressed at the outsides, and one layer of 10 mm side pressed in the core). The functional unit (FU) used as the base element for this assessment is one board of 2440 x 1220 x 20 mm (2,98 m2), with a weight of 41,7 kilograms (based on a density of 700 kg/m3).

Description of process step	amount	unit	ecocosts/FU	ecocosts/kg	percentage
1. Cultivation and harvesting from plantation					
Gasoline consumption	0,224	liter / FU	0,215	0,0052	1,8%
2. Transport from plantation to strip manufacturing facility					
Eco-costs of a 5 tons truck (EURO 3, transport of 23.1 FUs)	30	km / truck	0,094	0,0023	0,8%
3. Strip making	1,38	kWh/ FU	0,185	0,0044	1,6%
4. Transport from strip manufacturing facility to factory					
Eco-costs (28 tons truck EURO3, 300km)	12,51	ton.km / FU	0,488	0,0117	4,1%
5. Rough planing	8,62	kWh/ FU	1,153	0,0276	9,7%
6. Strip selection					
7. Carbonization	4,73	kWh/FU	0,633	0,0152	5,3%
8. Drying carbonized strips	9,66	kWh/FU	1,292	0,0310	10,9%
9. Fine planing	5,8	kWh/FU	0,776	0,0186	6,5%
10. Glue application (1-layer boards)					
Added amount of Melamine formaldehyde (dry condition)	0,483	kg / FU	0,541	0,013	4,5 %
11. Pressing strips to 1- layer board	1,89	kWh/FU	0,253	0,0061	2,1%
12. Sanding 1- layer board	1,62	kWh/FU	0,217	0,0052	1,8%
13. Glue application (3-layer board)					
Added amount Emulsion Poly Isocyanate (dry condition)	0,908	kg / FU	0,616	0,0148	5,2%
14. Pressing three layers to one board	1,65	kWh/FU	0,221	0,0053	1,9%
15. Sawing	0,29	kWh/FU	0,039	0,0009	0,3%
16. Sanding 3-layer board	0,86	kWh/FU	0,115	0,0028	1,0%
17. Dust absorption (during all steps)	8,67	kWh/FU	1,159	0,0278	9,7%
18. Transport from factory to harbour					
Eco-costs (28 tons truck EURO3, 300km)	12,51	ton.km / FU	0,488	0,0117	4,1%
19. Transport from harbour to harbour					
Eco-costs (20ft container in a transoceanic freight ship, 19208 km)	801	ton.km / FU	3,268	0,0784	27,5%
20. Transport from harbour to warehouse					
Eco-costs (28 tons truck EURO5, 115km)	4,80	ton.km / FU	0,153	0,0037	1,3%
TOTAL carbonized			11,90	0,285	100,0%

Table 2: Input data and results in eco-costs (€, cradle to gate) of carbonized 3-layer laminated bamboo board (consisting of two layers of 5 mm plain pressed at the outsides, and one layer of 10 mm side pressed in the core). The functional unit (FU) used as the base element for this assessment is one board of 2440 x 1220 x 20 mm (2,98 m2), with a weight of 41,7 kilograms (based on a density of 700 kg/m3).

Compression of rough bamboo fibers

A couple of years ago another production technology was developed, in which rough bamboo strips are put in resin after which, under high compression, they are pressed in moulds to form high density beams and panels. The result is an extremely hard (Brinell Hardness ≥ 9,5 kg/mm2 following EN 1534) material with a look that is hardly distinguished from tropical hardwood. Because of the high hardness it is ideally used in applications where this hardness is utilized, such as (top layers of) flooring and panels for table tops, but also for outdoor decking. Besides the good mechanical properties, another benefit of this production technology is that strips of less quality can be used as input material. Also this product is available in the colours natural (bleached input strips) or caramel (carbonized input strips). This type of bamboo product is also referred to as "High Density" or "Strand Woven Bamboo". A recent innovation is an outdoor variation of the High Density boards where the input strips are first thermally modified to increase the durability of the input materials to the highest class possible (class 1 according to EN 350). Due to the higher resin content (6,2% instead of 3,5%) and compression, this product has an ever higher density than the regular Strand Woven Bamboo boards (1200 kg/m3 instead of 1080 kg/m3). However, because of the additional thermal modification (electricity intensive process) and the increased resin content, the environmental impact of this product is larger than that of the regular Strand Woven Bamboo.

Figure 10: Strand Woven Bamboo beams are made by compressing rough bamboo fibres in moulds under very high pressure (photos MOSO International)

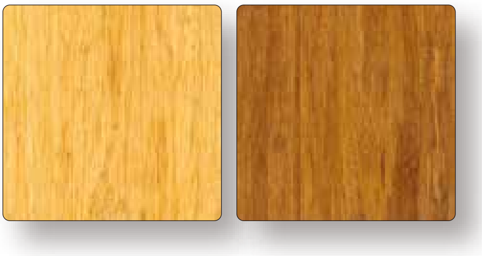


Figure 11: In the High Density or Strand Woven Bamboo style the bamboo nodes are hardly visible anymore (photos MOSO International).

Description of process step	amount	unit	CO2equ/FU	CO2equ/kg	percentage
1. Cultivation and harvesting of bamboo on sustainable managed plantations					
Gasoline consumption	0,0832	liter / FU	0,242	0,0096	1,0%
2. Transport from plantation to strip manufacturing facility					
Eco-costs of a 5 tons truck (EURO 3, transport of 23.1 FUs)	30	km / truck	0,262	0,0104	1,1%
3. Strip making	0,8	kWh/ FU	0,462	0,0183	2,0%
4. Transport from strip manufacturing facility to factory					
Eco-costs (28 tons truck EURO3, 300km)	7,44	ton.km / FU	1,376	0,0545	5,9%
5. Rough planing	5,28	kWh/ FU	3,048	0,1206	13,2%
6. Splitting strips in half	0,8	kWh/FU	0,462	0,0183	2,0%
7. Carbonization	2,8	kWh/FU	1,617	0,0640	7,0%
8. Drying carbonized strips	5,624	kWh/FU	3,247	0,1285	14,0%
9. Crushing strips	1,36	kWh/FU	0,785	0,0311	3,4%
10. Glue application					
Added amount of Melamine formaldehyde (dry condition)	1,68	kg / FU	2,672	0,1057	11,5%
11. Pressing strips to beam	2,32	kWh/FU	1,339	0,0530	5,8%
12. Activating glue in oven	2,8	kWh/FU	1,617	0,0640	7,0%
13. Sawing beams	0,352	kWh/FU	0,203	0,0080	0,9%
14. Sanding beams	0,188	kWh/FU	0,109	0,0043	0,5%
15. Transport from factory to harbour					
Eco-costs (28 tons truck EURO3, 300km)	7,44	ton.km / FU	1,376	0,0545	5,9%
16. Transport from harbour to harbour					
Eco-costs (19208km, 20ft container in a transoceanic freight ship)	476,8	ton.km / FU	3,843	0,1521	16,6%
17. Transport from harbour to warehouse					
Eco-costs (28 tons truck EURO5, 115km)	2,88	ton.km / FU	0,484	0,0191	2,1%
TOTAL carbonized			23,144	0,916	100,0%

Table 3: Input data and results in CO2 equivalent (carbon footprint, cradle to gate) of a carbonized Strand Woven Bamboo beam. The functional unit (FU) used as the base element for this assessment is one solid beam, gross size 1900 X 110 X 140mm, net size 1800 x 100 x 130mm with a weight of 25,3 kilograms (based on a density of 1080 kg/m3).

Description of process step	amount	unit	ecocosts/FU	ecocosts/kg	percentage
1. Cultivation and harvesting of bamboo on sustainable managed plantations					
Gasoline consumption	0,0832	liter / FU	0,08	0,0032	1,2%
2. Transport from plantation to strip manufacturing facility					
Eco-costs of a 5 tons truck (EURO3, transport of 61,5 FUs)	30	km / truck	0,035	0,0014	0,5%
3. Strip making	0,8	kWh/ FU	0,107	0,0042	1,6%
4. Transport from strip manufacturing facility to factory					
Eco-costs (28 tons truck EURO3, 300km)	7,44	ton.km / FU	0,290	0,0115	4,3%
5. Rough planing	5,28	kWh/ FU	0,706	0,0279	10,4%
6. Splitting strips in half	0,8	kWh/FU	0,107	0,0042	1,6%
7. Carbonization	2,8	kWh/FU	0,374	0,0148	5,5%
8. Drying carbonized strips	5,624	kWh/FU	0,752	0,0298	11,1%
9. Crushing strips	1,36	kWh/FU	0,182	0,0072	2,7%
10. Glue application					
Added amount of Phenol formaldehyde (wet condition)	1,68	kg / FU	1,074	0,0425	15,8%
11. Pressing strips to beam	2,32	kWh/FU	0,310	0,0123	4,6%
12. Activating glue in oven	2,8	kWh/FU	0,374	0,0148	5,5%
13. Sawing beams	0,352	kWh/FU	0,047	0,0019	0,7%
14. Sanding beams	0,188	kWh/FU	0,025	0,0010	0,4%
15. Transport from factory to harbour					
Eco-costs (28 tons truck EURO3, 300km)	7,44	ton.km / FU	0,290	0,0115	4,3%
16. Transport from harbour to harbour					
Eco-costs (19208km, 20ft container in a transoceanic freight ship)	476,8	ton.km / FU	1,945	0,077	28,6%
17. Transport from harbour to warehouse					
Eco-costs (28 tons truck EURO5, 115km)	2,88	ton.km / FU	0,092	0,0036	1,4%
TOTAL carbonized			6,793	0,269	100,0%

Table 4: Input data and results in eco-costs (€, cradle to gate) of a carbonized Strand Woven Bamboo beam. The functional unit (FU) used as the base element for this assessment is one solid beam, gross size 1900 X 110 X 140mm, net size 1800 x 100 x 130mm with a weight of 25,3 kilograms (based on a density of 1080 kg/m3).

Flattened bamboo

Another very recent technology is based on cutting the original bamboo stem longitudinally in half after which it is flattened through a special steam treatment process, after which it can be used for the production of flooring board. As with the Strand Woven Bamboo technology, a benefit of the flattened bamboo technology is that a larger portion of the bamboo stem can be used as input material for high quality products (usually the whole 8m stem can be used). The best flattened stem segments (2,66m length) are used as toplayer for the flooring boards because of the hardness (the outer layer of the bamboo stem is extremely hard, Brinell Hardness ≥ 9,5 kg/mm2 (EN 1534), whereas the lower quality boards (small visual defects, smaller width) are used as middle or bottom layer of the 3ply flooring board. This production process therefore has a higher production efficiency (larger part of the input stem can be used combined with less waste) and less glue is required as for plybamboo (laminating strips) and Strand Woven Bamboo (compression moulding) making this the best-performing alternative in the assessed product range based on a cradle to gate scenario (for more information see chapter 7 and 8).

Figure 12: Flattened bamboo features the original bark of the bamboo stem as toplayer (photos MOSO International).

Description of process step	amount	unit	CO2equ/FU	CO2equ/kg	percentage
1. Cultivation and harvesting from sustainably managed plantation					
Gasoline consumption	0,006	liter / FU	0,016	0,0090	1,5%
2. Transport from plantation to factory					
Eco-costs of a 5 tons truck (EURO3, transport of 780 FUs)	120	km / truck	0,087	0,0478	7,7%
3. Cutting stem segments longitudinally in half	0,0066	kWh/ FU	0,004	0,0021	0,3%
4. Removing internal parts of the stem	0,079	kWh/ FU	0,045	0,0250	4,0%
5. Removing outside parts of the stem	0,026	kWh/ FU	0,015	0,0083	1,3%
6. Shortening	0,006	kWh/FU	0,004	0,0020	0,3%
7. Softening – vapour treatment	0,013	kWh/FU	0,007	0,0040	0,6%
8. Flattening boards	0,063	kWh/FU	0,036	0,0200	3,2%
9. Finalizing shape - press	0,079	kWh/FU	0,045	0,0250	4,0%
10. Surface planing (2 sides)	0,070	kWh/ FU	0,041	0,0223	3,6%
11. Drying flat boards	0,459	kWh/FU	0,265	0,1457	23,5%
12. Cutting to final width	0,0258	kWh/FU	0,015	0,0082	1,3%
13a. Glue application					
Added amount Emulsion Poly Isocyanate (dry condition)	0,023	kg / FU	0,037	0,0206	3,3%
13b. Pressing three layers to one board	0,117	kWh/FU	0,067	0,0370	6,0%
14. Balancing (climate chamber)	0,027	kWh/FU	0,015	0,0085	1,4%
15. Cutting to final length	0,0158	kWh/FU	0,009	0,0050	0,8%
16. Transport from factory to harbour					
Eco-costs (28 tons truck EURO3, 300km)	0,546	ton.km / FU	0,101	0,0555	8,9%
17. Transport from harbour to harbour					
Eco-costs (20ft container in a transoceanic freight ship, 19208km)	35	ton.km / FU	0,282	0,1548	25,0%
18. Transport from harbour to warehouse					
Eco-costs (28 tons truck EURO5, 115km)	0,21	ton.km / FU	0,035	0,0193	3,1%
TOTAL			1,13	0,620	100,0%

Table 5: Input data and results in CO2 equivalent (carbon footprint, cradle to gate) of a flattened bamboo board. The functional unit (FU) used as the base element for this assessment is one 3ply flooring board, 1210x125x18mm with a weight of 1,819 kilograms.

Description of process step	amount	unit	ecocosts/FU	ecocosts/kg	percentage
1. Cultivation and harvesting from sustainably managed plantation					
Gasoline consumption	0,006	liter / FU	0,005	0,0030	1,4%
2. Transport from plantation to factory					
Eco-costs of a 5 tons truck (EURO3, transport of 780 FUs)	120	km / truck	0,054	0,0300	14,4%
3. Cutting stem segments longitudinally in half	0,0066	kWh/ FU	0,001	0,0005	0,2%
4. Removing internal parts of the stem	0,079	kWh/ FU	0,011	0,0058	2,8%
5. Removing outside parts of the stem	0,026	kWh/ FU	0,004	0,0019	0,9%
6. Shortening	0,006	kWh/FU	0,001	0,0005	0,2%
7. Softening – vapour treatment	0,013	kWh/FU	0,002	0,0009	0,4%
8. Flattening boards	0,063	kWh/FU	0,008	0,0046	2,2%
9. Finalizing shape - press	0,079	kWh/FU	0,011	0,0058	2,8%
10. Surface planing (2 sides)	0,070	kWh/ FU	0,009	0,0052	2,5%
11. Drying flat boards	0,459	kWh/FU	0,061	0,0337	16,2%
12. Cutting to final width	0,0258	kWh/FU	0,003	0,0019	0,9%
13a. Glue application					
Added amount Emulsion Poly Isocyanate (dry condition)	0,023	kg / FU	0,016	0,0086	4,1%
13b. Pressing three layers to one board	0,117	kWh/FU	0,016	0,0086	4,1%
14. Balancing (climate chamber)	0,027	kWh/FU	0,004	0,0020	0,9%
15. Cutting to final length	0,0158	kWh/FU	0,002	0,0012	0,6%
16. Transport from factory to harbour					
Eco-costs (28 tons truck EURO3, 300km)	0,546	ton.km / FU	0,021	0,0117	5,6%
17. Transport from harbour to harbour					
Eco-costs (20ft container in a transoceanic freight ship, 19208km)	35	ton.km / FU	0,143	0,0784	37,7%
18. Transport from harbour to warehouse					
Eco-costs (28 tons truck EURO5, 115km)	0,21	ton.km / FU	0,007	0,0037	1,8%
TOTAL			0,38	0,208	100,0%

Table 6: Input data and results in eco-costs (€, cradle to gate) of a flattened bamboo board. The functional unit (FU) used as the base element for this assessment is one 3ply flooring board, 1210x125x18mm with a weight of 1,819 kilograms.

5 End-of-life calculations on bamboo products

As was explained in chapter 3, a credit can be ‘earned’ for avoided fossil fuels if the bamboo (or any other bio-product like wood) is burnt for electricity or heat.

In the Netherlands and several other Western European Countries, wood and bamboo are separated from other waste and ends up in an electrical power plant. Although the efficiency of a modern coal-fired electrical power plant is highest, i.e. 45% (IEA 2007), current practice in Western Europe is that biomass is bought by energy providers and combusted in smaller electrical power plants specializing in biomass with an approx. 30% lower efficiency than the large coal plants. Furthermore, it is estimated that approximately 10% perishes in nature (“landfill”), as specified in the NEN 8006 on LCA.

The end-of-life credit for electricity production from bamboo waste is (data from the Idemat database: “Idemat2014 Hardwood 12% MC, Bamboo, Cork, combustion in small elec. power plant”):

- carbon footprint: 0,782 kgCO2 per kg of bamboo waste
- eco-costs: 0,147 € per kg of bamboo waste

In this report we assume that 90% of the bamboo products will be combusted for production of electricity and/or heat, leading to a credit of:

- carbon footprint: 0,782 x 0,9 = 0,704 kgCO2 per kg of bamboo product (MC 12%)
- eco-costs: 0,147 x 0,9 = 0,132 € eco-costs per kg of bamboo product (MC 12%).

Although the above scores are according to the formal LCA (according to ISO 14040 and 14044, and according to the European LCA manual (EC-JRC 2010), the effects of the carbon sequestration on a global level must be taken into account as well before the final result can be calculated. This is dealt with in the next two chapters.

6 Calculation of carbon sequestration in forests and buildings

Note: the calculation structure in this chapter is similar to the calculation structure of section 6 of Vogtländer et al. (2014); however, some detailed data have been updated.

As has been explained in Chapter 3, the extra global carbon sequestration is proportional to the growth of the market for bamboo products, leading to more volume of bamboo in plantations as well as in durable bamboo products in the building industry.

The calculation of carbon sequestration caused by land-use change and additional application of bamboo products in the building industry is done in 5 steps (the calculation is an update of the calculation in Vogtländer et al. (2014):

1. the calculation of the relationship (ratio) of carbon stored in forests and carbon stored in end-products (Plybamboo, Strand Woven Bamboo, Flattened Bamboo); this first step is in compliance with baseline LCA
2. the calculation of a land-use change correction factor (to cope with the fact that there was another type of biomass before the area was changed to forests / plantations); this step is in compliance with the IPCC standards
3. the calculation of the extra stored carbon in forests and plantations (see Fig. 4 in chapter 3), because of growth of bamboo production, and its allocation to the end-products; this step, and the way of allocation, is deemed more realistic than the credits for temporary carbon storage in PAS 2050 and the ILCD handbook. For more details is referred to Vogtländer et al. (2014).
4. the calculation of the extra stored carbon in the building industry, because of growth of the volume; this step is in compliance with PAS 2050 and the ILCD handbook optional credit
5. the final calculation of the total result of carbon sequestration: the multiplication of the results of step 1, 2, 3, plus the result of step 4.

Below for each step the detailed calculations are provided for the Chinese bamboo production situation. The scope of the calculation is the carbon sequestration in industrial bamboo products from China based on cradle-to-grave, excluding emissions from forest management equipment, product manufacturing, transport, and end-of-life operations (a so called “streamlined” LCA approach). The geographical system boundary is China, as defined in FAO (2010).

Step 1. Calculation of the carbon ratio.

One kg of a bamboo end-product relates to many kg of biomass in the bamboo plantation:

- 1 kg biomass, dry matter (d.m.) above the ground in the bamboo plantation, on average is equivalent to 0,42 kg of bamboo in the end-product, see also figure 21 in Annex II, for more information on the processing efficiency of the various bamboo products is referred to van der Lugt (2008).
- 0,42 kg d.m. of bamboo, is used in 0,425 kg d.m. flattened bamboo (the resin content is on average approx 1,3 % of the weight of flattened bamboo), 0,425 kg d.m. plybamboo (the resin content is on average approx 2,5 % of the weight of plybamboo), 0,435 kg d.m. Strand Woven Bamboo - SWB (the resin content is 3,5 % of the weight of SWB) and for thermally modified “outdoor” SWB 0,446 kg d.m.
- 1 kg biomass above the ground in the bamboo plantation is equivalent to 3,1 kg d.m. biomass above + below the ground, since bamboo has a vast root system[1] this number is in line with various recent studies bundled in Lou Yiping et al. (2010).

Note that unlike trees, which are usually clear cut, the regular and selective harvesting of bamboo culms doesn’t kill the plant or damage the ecosystem, and below-ground carbon in the soil and rhizome is not emitted as the bamboo forest continues to live after harvest (Kuehl et al. 2011).

- 1 kg d.m. of flattened bamboo originates from 3,1/0,425=7,29 kg d.m. biomass in the bamboo plantation, 1 kg d.m. of plybamboo originates from 3,1/0,431=7,20 kg d.m. biomass in the plantation, 1 kg d.m. indoor SWB originates from 3,1/0.435=7,13 kg d.m. biomass in the bamboo plantation and 1 kg outdoor SWB to 3,1/0,446=6,95 kg d.m. biomass.
- The carbon content is 0,5 kg C per 1 kg bamboo (Aalde et al. 2006, Verchot et al. 2006).
- Therefore, 1 kg d.m. flattened bamboo is equivalent to the storage of 7,29×0,5=3,64 kg carbon in the plantation, 1 kg d.m. plybamboo is equivalent to the storage of 7,20×0,5=3,60 kg carbon in the plantation, 1 kg d.m. indoor SWB is equivalent to the storage of 7,13×0,50=3,57 kg carbon in the plantation, for outdoor SWB this relates to 6.95 x0.5 = 3.48 kg carbon in the plantation.

The result of step 1:

- 1 kg d.m. flattened bamboo is related to 3,64 × 3,67=**13,37 kg CO2** storage in the plantation. Note: the factor 3,67 stems from the molar weight ratio of CO2 and C.
- 1 kg d.m. plybamboo is related to 3,60×3,67=**13,21 kg CO2** storage in the plantation.
- 1 kg d.m. indoor SWB is related to 3,57×3,67=**13,09 kg CO2** storage in the plantation for the outdoor version this is 3,48x3,67 = **12,75 kg CO2** storage in the plantation.

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[1] Besides in the trunks, branches and shrub, there is CO2 stored below ground in the soil and roots of a plantation. Zhou and Jiang (2004) found that, for a medium intensity managed Moso bamboo plantation in Lin’an, Zhejiang province, the distribution of biomass above ground versus below ground is 32,2% and 68,8% respectively.

Step 2. Calculation of the land-use change correction factor.

This second step in the calculation is related with the land-use change: before the afforestation, the land had also stored biomass. So the "Tier 2 Gain-Loss Method" (Verchot et al. 2006) of the IPCC has to be applied (it must be mentioned that this method is not described in the ILCD Handbook, Annex B (EC-JRC 2010), however, it is fully in line with the requirement of section 7.4.4.1 page 234). The essence of this gain-loss method is a comparison of the steady state *before and after* the land-use change.

For Chinese bamboo, it is assumed that the additional permanent plantations are established on grassland and do not come at the expense of natural tree forests. This is a plausible assumption as a large portion of the Moso bamboo resources comes from the industrialised provinces around Shanghai (Zhejiang, Fujian, Anhui, Jiangxi). Furthermore, this assumption fits well in the current policy for afforestation and natural forest protection of the Chinese government controlled by the Chinese State Forestry Administration. More information on this issue can be found at the website of Chinese State Forestry (CSF 2013).

The "Total above-ground and below-ground non-woody biomass" is 7,5 tonnes d.m./ha (it ranges from 6,5 to 8,5) with a carbon content of 47% (Verchot et al. 2006).
The biomass of bamboo plantations is 35,8 x 3,1 = 111 tonnes[2] d.m./ha for biomass above + below the ground (Van der Lugt 2009a&b, Zhou and Jiang 2004), and a carbon content of 50%.
The land-use change correction factor for afforestation is therefore:

{(111 x 0,50) – (7,5 x 0,47)}/(111 x 0,50) = **0,936**

Much of the extra Chinese bamboo production comes from better management (Lou Yiping et al. 2010) of existing bamboo forests. In such a case the land-use change correction factor is 1 for the extra bamboo production.

Step 3. Calculation of extra stored carbon in forests and its allocation.

According to van der Lugt and Lobovikov (2008), annual growth of the market for industrial bamboo products in EU and China ranges between 17% to 25%. However, the establishment of new plantations often does not directly follow increase in market demand but is following the market growth with a delay. This phenomenon also becomes clear from the 7th Chinese National Forestry Inventory (State Forestry Administration of P.R. China 2010) where it is shown that the area of bamboo resources in China in 2004-2008 has grown from 4,84 million ha to 5,38 million ha in 2008, thus a growth of 11,18% in 5 years which refers to an annual growth of 2,24%. Note that the growth of tree forest area in China lies at a similar level (11,74%) with a growth of 174,91 million ha to 195,45 million ha in the same period (2004-2008).

2 *Note that Lou Yiping et al (2010) have reported higher outputs (101.6-288.5 tC/ha).*

Very recent figures (INBAR, 2014) show that the growth of bamboo forests and plantations in China is accelerating in recent years, which results in a total area of 7,37 million ha in 2015. This corresponds with an annual growth of approximately 5% per year[3].

Given the high GDP growth of the Chinese economy (approximately 7.5%), a **5%** increase of bamboo production seems to be a safe side estimation for the calculation of the extra stored carbon in bamboo plantations.

The related growth of yearly extra carbon storage in the plantation is to be allocated to the total production of bamboo products: of every kg of bamboo, **0,05 kg** is related to the extra plantations which are required to cope with the market growth, and add to the global carbon sequestration.

Step 4. Calculation of the extra stored carbon in buildings.

The extra carbon sequestration in buildings is related to the bamboo products minus “application losses”, which we estimate at 10%. Taking into account the resin content in the end-product (1,3% for flattened bamboo, 2,5% for plybamboo, 3,5% for indoor SWB and 6,2% for outdoor SWB), this results in:

- 0,987 x 0,9 x 0,5 x 3,67 = 1,63 kg biogenic CO2 storage in the buildings per 1 kg d.m. flattened bamboo. The extra storage, related to the market growth in step 3, results in the extra carbon sequestration of 1,63 x 0,05 = **0,082 kg CO2** per kg d.m. flattened bamboo.
- 0,975 x 0,9 x 0,5 x 3,67 = 1,61 kg biogenic CO2 storage in the buildings per 1 kg d.m. plybamboo. The extra storage, related to the market growth in step 3, results in the extra carbon sequestration of 1,61 x 0,05 = **0,081 kg CO2** per kg d.m. plybamboo.
- 0,965 x 0,9 x 0,5 x 3,67 = 1,59 kg biogenic CO2 storage in the buildings per 1 kg d.m. indoor SWB. The extra storage, related to the market growth in step 3, results in the extra carbon sequestration of 1,59 x 0,05 = **0,080 kg CO2** per kg d.m. indoor SWB.
- 0,938 x 0,9 x 0,5 x 3,67 = 1,55 kg biogenic CO2 storage in the buildings per 1 kg d.m. outdoor SWB. The extra storage, related to the market growth in step 3, results in the extra carbon sequestration of 1,55 x 0,05 = **0,077 kg CO2** per kg d.m. outdoor SWB.

Step 5. Calculation of the total result.

The overall effect on carbon sequestration caused by land-use change can be calculated now by the multiplication of the results of step 1, 2, 3, plus the result of step 4:

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[3] *It must be mentioned here that this growth does not always require extra agricultural land. In fact in the national bamboo development plan, one of the main short term (2011-2015) goals is to improve the quality (and therefore yield) of existing 1,9 mio existing forests (INBAR 2014). Moreover, due to the extensive root system bamboo is planted in areas where farming is not feasible, e.g., at slopes for erosion prevention, and for rehabilitating degraded land and re-establishing functioning and productive ecosystems by improving soil quality and restoring the water table (Kuehl and Lou Yping 2011)*

- carbon sequestration = 13,37 x 0,936 x 0,05 + 0,082 = **0,707 kg CO2** per kg d.m. flattened bamboo (**0,637 kg CO2** at 10% MC); in eco-costs this relates to €0,095 per kg d.m. flattened bamboo (€0,086 at 10%MC).
- carbon sequestration = 13,21 x 0,936 x 0,05 + 0,081 = **0,699 kg CO2** per kg d.m. plybamboo (**0,629 kg CO2** at 10% MC); in eco-costs this relates to €0,094 per kg d.m. plybamboo (€0,085 at 10%MC).
- carbon sequestration = 13,09 x 0,936 x 0,05 + 0,080 = **0,692 kg CO2** per kg d.m. SWB indoor (**0,623 kg CO2** at 10% MC); in eco-costs this relates to €0,093 per kg d.m. indoor SWB (€0,084 at 10%MC).
- carbon sequestration = 12,75 x 0,936 x 0,05 + 0,077 = **0,674 kg CO2** per kg d.m. SWB outdoor (**0,607 kg CO2** at 10% MC); in eco-costs this relates to €0,091 per kg d.m. outdoor SWB (€0,082 at 10%MC).

The amounts mentioned above can be allocated as 'credit' in the LCA calculation (in addition to the end-of-life credit in the case of combustion in electrical power plants, as explained in chapter 5).

Note that these carbon sequestration credits for bamboo as a result of land change are higher than for wood: European softwood acquires a credit for carbon sequestration as a result of land change of **0,17 kg** CO2 per kg softwood 10% MC, for detailed calculations is referred to Vogtländer et al. (2014).

There are several reasons why Chinese bamboo acquires a higher credit for carbon sequestration as a result of land use compared to softwood:

- the root – shoot ratio of bamboo is much higher than for wood; as a result of the extensive root (rhizome) system, bamboo stores considerably more CO2 under the ground in the rhizomes as well as the surrounding soil.
- The higher reforestation rate in China with bamboo than in Europe with softwood. This is the result of the quicker market growth of bamboo products compared to wood products.

Due to the high growing speed the establishment time of new bamboo plantations is a lot shorter than for wood forests while bamboo plantations can also be planted in locations where it is impossible to plant trees (e.g. degraded slopes), making it a good crop for reforestation.

Results: Tables on combined cradle-to-grave calculations, including carbon sequestration

The calculations of the various tables of Chapter 4 have been made for the different production variations (styles), colours and layer types. The tables below show the combined results of the calculations of the LCA (chapter 4 and 5) and the carbon sequestration (chapter 6) for the product portfolio of MOSO International BV.

Note: SP= Side Pressed, PP= Plain Pressed, DT= Density / Compressed, N= Natural (bleached), C= Caramel (Carbonized), E0= produced with glues with No Added Formaldehyde (Formaldehyde emission: Class E0, < 0,025 mg/m3).

Outdoor					Carbon Footprint (CO2eq) per kg final product				Eco-costs (€) per kg final product			
	Thickness(mm)	type	style	Color	**PRODUCTION cradle to gate** CO2equ/kg	**End-of-life** CO2equ/kg	**CO2 storage** CO2equ/kg	**CO2 total** CO2equ/kg	**PRODUCTION cradle to gate** Euro/kg	**End-of-life** Euro/kg	**eco-costs CO2 storage** Euro/kg	**eco-costs Total** Euro/kg
Decking & cladding (MOSO Bamboo X-treme)	20		DT	C	1,193	-0,704	-0,607	-0,1176	0,356	-0,132	-0,082	0,142

Flooring					Carbon Footprint (CO2eq) per kg final product				Eco-costs (€) per kg final product			
	Thickness(mm)	type	style	Color	**PRODUCTION cradle to gate** CO2equ/kg	**End-of-life** CO2equ/kg	**CO2 storage** CO2equ/kg	**CO2 total** CO2equ/kg	**PRODUCTION cradle to gate** Euro/kg	**End-of-life** Euro/kg	**eco-costs CO2 storage** Euro/kg	**eco-costs Total** Euro/kg
Solid strip (MOSO Purebamboo)	15		SP	N	0,925	-0,704	-0,629	-0,4084	0,257	-0,132	-0,085	0,040
	15	E0	SP	N	0,911	-0,704	-0,629	-0,4217	0,253	-0,132	-0,085	0,036
	15		PP	N	0,951	-0,704	-0,629	-0,3822	0,268	-0,132	-0,085	0,051
	15	E0	PP	N	0,945	-0,704	-0,629	-0,3884	0,266	-0,132	-0,085	0,049
	15		SP	C	0,964	-0,704	-0,629	-0,3690	0,265	-0,132	-0,085	0,048
	15	E0	SP	C	0,951	-0,704	-0,629	-0,3824	0,262	-0,132	-0,085	0,045
	15		PP	C	0,990	-0,704	-0,629	-0,3429	0,276	-0,132	-0,085	0,059
	15	E0	PP	C	0,984	-0,704	-0,629	-0,3491	0,275	-0,132	-0,085	0,058
	15		DT	C	1,048	-0,704	-0,623	-0,2795	0,301	-0,132	-0,084	0,085
	15		DT	N	1,008	-0,704	-0,623	-0,3194	0,292	-0,132	-0,084	0,076
Solid wide board (3 ply) (MOSO Bamboo Elite)	15		SP	N	1,015	-0,704	-0,629	-0,3176	0,286	-0,132	-0,085	0,069
	15	E0	SP	N	0,957	-0,704	-0,629	-0,3764	0,271	-0,132	-0,085	0,054
	15		PP	N	1,006	-0,704	-0,629	-0,3266	0,283	-0,132	-0,085	0,066
	15	E0	PP	N	0,952	-0,704	-0,629	-0,3807	0,269	-0,132	-0,085	0,053
	15		SP	C	1,055	-0,704	-0,629	-0,2783	0,294	-0,132	-0,085	0,077
	15	E0	SP	C	0,996	-0,704	-0,629	-0,3371	0,280	-0,132	-0,085	0,063
	15		PP	C	1,046	-0,704	-0,629	-0,2873	0.291	-0,132	-0,085	0,074
	15	E0	PP	C	0,992	-0,704	-0,629	-0,3414	0.278	-0,132	-0,085	0,061
	13		DT	N	1,004	-0,704	-0,623	-0,3227	0.288	-0,132	-0,084	0,071
	13		DT	C	1,042	-0,704	-0,623	-0,2846	0.296	-0,132	-0,084	0,080

Flooring

Flooring	Thickness(mm)	type	style	Color	Carbon Footprint (CO2eq) per kg final product: PRODUCTION cradle to gate CO2equ/kg	End-of-life CO2equ/kg	CO2 storage CO2equ/kg	CO2 total CO2equ/kg	Eco-costs (€) per kg final product: PRODUCTION cradle to gate Euro/kg	End-of-life Euro/kg	eco-costs CO2 storage Euro/kg	eco-costs Total Euro/kg
2-Ply flooring (MOSO Bamboo Supreme)	10		SP	N	0,876	-0,704	-0,629	-0,4573	0,248	-0,132	-0,085	0,031
	10	E0	SP	N	0,870	-0,704	-0,629	-0,4626	0,247	-0,132	-0,085	0,030
	10		PP	N	0,871	-0,704	-0,629	-0,4620	0,246	-0,132	-0,085	0,029
	10	E0	PP	N	0,868	-0,704	-0,629	-0,4653	0,246	-0,132	-0,085	0,029
	10		SP	C	0,915	-0,704	-0,629	-0,4183	0,256	-0,132	-0,085	0,039
	10	E0	SP	C	0,909	-0,704	-0,629	-0,4237	0,248	-0,132	-0,085	0,031
	10		PP	C	0,910	-0,704	-0,629	-0,4232	0,255	-0,132	-0,085	0,038
	10	E0	PP	C	0,907	-0,704	-0,629	-0,4265	0,247	-0,132	-0,085	0,030
	10		DT	N	0,939	-0,704	-0,623	-0,3883	0,270	-0,132	-0,084	0,054
	10		DT	C	0,978	-0,704	-0,623	-0,3491	0,279	-0,132	-0,084	0,062
On-edge / Industrial floor (MOSO Bamboo Industriale)	10, 15		SP	N	0,816	-0,704	-0,629	-0,5168	0,229	-0,132	-0,085	0,012
	10, 15		SP	C	0,856	-0,704	-0,629	-0,4775	0,238	-0,132	-0,085	0,021
	10		DT	N	0,971	-0,704	-0,623	-0,3556	0,283	-0,132	-0,084	0,067
	10		DT	C	1,010	-0,704	-0,623	-0,3170	0,291	-0,132	-0,084	0,075
Flattened bamboo (3 ply) (MOSO Bamboo Forest)	18		EO		0,620	-0,704	-0,637	-0,7208	0,208	-0,132	-0,086	-0,010

Panels & Beams

Panels & Beams	Thickness(mm)	type	style	Color	Carbon Footprint (CO2eq) per kg final product: PRODUCTION cradle to gate CO2equ/kg	End-of-life CO2equ/kg	CO2 storage CO2equ/kg	CO2 total CO2equ/kg	Eco-costs (€) per kg final product: PRODUCTION cradle to gate Euro/kg	End-of-life Euro/kg	eco-costs CO2 storage Euro/kg	eco-costs Total Euro/kg
1 ply panel	3, 5		SP	N	0,925	-0,704	-0,629	-0,4084	0,257	-0,132	-0,085	0,040
	3, 5	E0	SP	N	0,911	-0,704	-0,629	-0,4217	0,253	-0,132	-0,085	0,036
	3, 5		PP	N	0,915	-0,704	-0,629	-0,4180	0,253	-0,132	-0,085	0,036
	3, 5	E0	PP	N	0,907	-0,704	-0,629	-0,4263	0,251	-0,132	-0,085	0,034
	3, 5		SP	C	0,964	-0,704	-0,629	-0,3690	0,265	-0,132	-0,085	0,048
	3, 5	E0	SP	C	0,951	-0,704	-0,629	-0,3824	0,262	-0,132	-0,085	0,045
	3, 5		PP	C	0,954	-0,704	-0,629	-0,3786	0,262	-0,132	-0,085	0,045
	3, 5	E0	PP	C	0,946	-0,704	-0,629	-0,3869	0,260	-0,132	-0,085	0,043
	4		DT	N	1,008	-0,704	-0,623	-0,3194	0,292	-0,132	-0,084	0,076
	4		DT	C	1,048	-0,704	-0,623	-0,2795	0,301	-0,132	-0,084	0,085
multi-layer panel	16, 20, 30, 40		SP	N	0,995	-0,704	-0,629	-0,3383	0,282	-0,132	-0,085	0,065
	16, 20, 30, 40	E0	SP	N	0,965	-0,704	-0,629	-0,3676	0,275	-0,132	-0,085	0,058
	16, 20, 30, 40		PP	N	0,979	-0,704	-0,629	-0,3543	0,277	-0,132	-0,085	0,060
	16, 20, 30, 40	E0	PP	N	0,958	-0,704	-0,629	-0,3752	0,272	-0,132	-0,085	0,055
	16, 20, 30, 40		SP	C	1,034	-0,704	-0,629	-0,2990	0,291	-0,132	-0,085	0,074
	16, 20, 30, 40	E0	SP	C	1,005	-0,704	-0,629	-0,3283	0,284	-0,132	-0,085	0,067
	16, 20, 30, 40		PP	C	1,018	-0,704	-0,629	-0,3150	0,285	-0,132	-0,085	0,069
	16, 20, 30, 40	E0	PP	C	0,997	-0,704	-0,629	-0,3359	0,280	-0,132	-0,085	0,063
	20, 38		DT	N	0,976	-0,704	-0,623	-0,3513	0,289	-0,132	-0,084	0,073
	20, 38		DT	C	1,015	-0,704	-0,623	-0,3123	0,297	-0,132	-0,084	0,081
Veneer	0.6		SP	N	1,110	-0,704	-0,629	-0,2231	0,300	-0,132	-0,085	0,083
	0.6	E0	SP	N	1,106	-0,704	-0,629	-0,2271	0,292	-0,132	-0,085	0,075
	0.6		PP	N	1,330	-0,704	-0,629	-0,0032	0,352	-0,132	-0,085	0,135
	0.6	E0	PP	N	1,325	-0,704	-0,629	-0,0079	0,335	-0,132	-0,085	0,118
	0.6		SP	C	1,153	-0,704	-0,629	-0,1799	0,310	-0,132	-0,085	0,093
	0.6	E0	SP	C	1,149	-0,704	-0,629	-0,1839	0,301	-0,132	-0,085	0,084
	0.6		PP	C	1,381	-0,704	-0,629	0,0478	0,300	-0,132	-0,085	0,083
	0.6	E0	PP	C	1,376	-0,704	-0,629	0,0431	0,346	-0,132	-0,085	0,129
Solid joist	55, 60, 72, 100		SP	N	1,020	-0,704	-0,629	-0,3130	0,266	-0,132	-0,085	0,049
	55, 60, 72, 100	E0	SP	N	0,991	-0,704	-0,629	-0,3423	0,266	-0,132	-0,085	0,049
	55, 60, 72, 100		SP	C	1,059	-0,704	-0,629	-0,2737	0,2742	-0,132	-0,085	0,057
	55, 60, 72, 100	E0	SP	C	1,030	-0,704	-0,629	-0,3031	0,2742	-0,132	-0,085	0,057
	60, 72, 100		DT	N	0,878	-0,704	-0,623	-0,4485	0,261	-0,132	-0,084	0,045
	60, 72, 100		DT	C	0,916	-0,704	-0,623	-0,4111	0,269	-0,132	-0,084	0,053

Conclusion & Discussion 8

In this study, a Life-cycle Assessment and carbon footprint was executed for industrial bamboo products following a best-case scenario based on the production figures of MOSO International BV, in which the effect of carbon sequestration was included. From the results, shown in chapter 7, it can be concluded that almost all industrial bamboo products, based on use in Europe have a negative number, i.e., are CO2 negative. Apparently the credits for bio-energy production during the end-of-life (EoL) phase and carbon sequestration as a result of land change, outweigh the emissions during production in China and shipping the bamboo products to Europe, see figure 13.

The only assessed industrial bamboo product which is not CO2 negative is plain pressed carbonised veneer. In general, veneer has a relatively high environmental impact because of the thin thickness of the veneer sheets resulting in more resin consumption per sheet (especially in case of multi layered veneer) and high fragility of the veneer, especially in plain pressed form, resulting in a lower processing efficiency (more waste). However, the side pressed versions of the veneer are CO2 negative and with some small efficiency improvements (e.g., recycling waste) this is also possible in the near future for plain pressed caramel veneer.

It is interesting to analyse the difference between the three main production technologies flattened bamboo, Plybamboo and Strand Woven Bamboo - SWB (indoor & outdoor) over the full life cycle, see figure 13. Although the comparison is between different functional units (flooring, beams, decking) the graph gives a good indication how the various technologies compare to one another per kg of final product in terms of environmental impact.

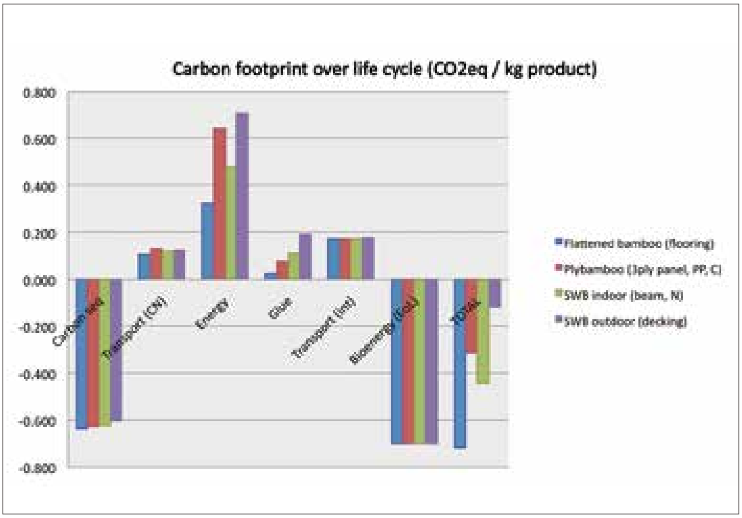

Figure 13: Carbon footprint over life cycle (kgCO2eq / kg product), for various industrial bamboo products based on different production technologies.

From the graph, it becomes clear that although all alternatives are CO2 negative over the full life cycle, there are significant differences between the various production technologies:

- Because of the relatively short production process, high efficiency (large part of the input stem can be used) and the low resin content, the flattened bamboo boards are clearly the best choice from an environmental point of view.
- Not surprisingly, due to the relatively high energy consumption because of the thermal modification and the higher resin content, the outdoor SWB performs worse than indoor SWB. However the outdoor SWB is the only bamboo product which has the durability performance to be used in outdoor applications where it can substitute tropical hardwood (see also comparison in tables 7 & 8).
- Based on the carbon footprint per kg product, the indoor SWB material seems to perform better than the Plybamboo material, which seems strange because of the higher resin content. This can be explained by the shorter production process as well as the absence of a dust absorption system in the assessed SWB factory resulting in lower energy consumption per kg material.

Note that in the case of eco-costs the outcomes are similar, with slight differences as the impact of sea transport is more significant as well as the impact of some resins, see figure 14 below.

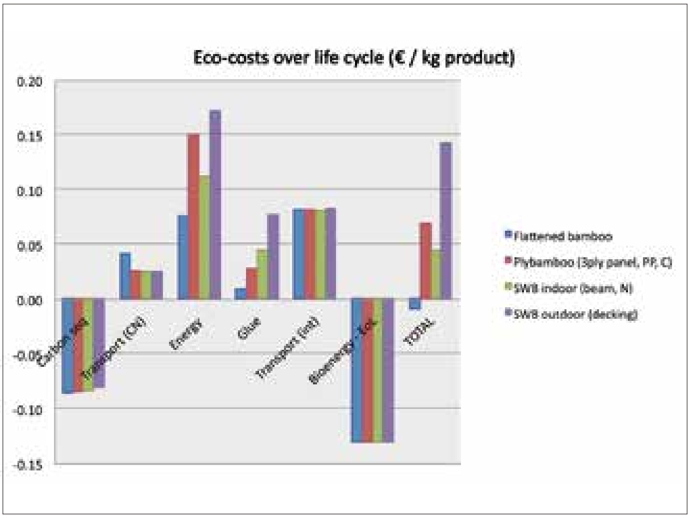

Figure 14: Eco-costs over life cycle (kgCO2eq / kg product), for various industrial bamboo products based on different production technologies.

If we look at the process categories we can make the following conclusions from an environmental point of view:

- **Energy consumption** in processing the industrial bamboo products provides the largest contribution to the environmental impact, being responsible for 36 – 53% (eco-costs) and 52-63% (carbon footprint) of the total eco-burden. Since the bamboo processing facilities in general use biomass (bamboo waste) for heat, the energy is only electricity from the local grid. This electricity from the grid might be replaced by electricity from a combined power generator (bamboo waste is abundantly available) at the production facility, or on-site production of solar energy.

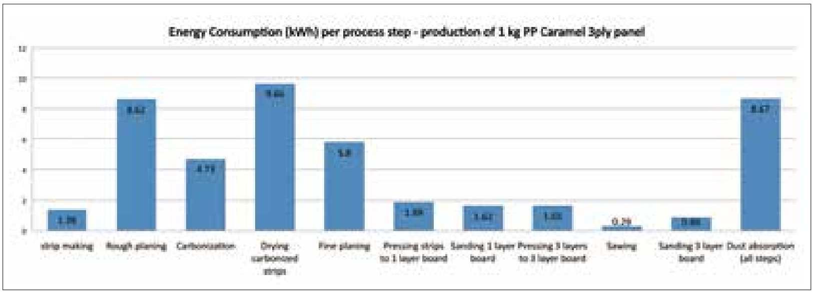

Figure 15: Carbon footprint for electricity consumption over life cycle (kgCO2eq / kg product), in this case for a 3ply carbonized solid bamboo panel.

- After energy consumption, **international sea transport** has the largest influence on the environmental impact, being responsible for 15-25% (carbon footprint) and even 28-37% (eco-costs) of the eco-burden of the industrial bamboo products, with relatively the largest impact on the flattened bamboo because of the lower energy and resin content of this product. In case of local consumption (China) this additional eco-burden can be directly subtracted from the total. For the European market, this is of course not a possibility, but closer sourcing (e.g., from Ethiopia with its large bamboo resource) could be an option for the near future improving the environmental impact (the electricity mix of Ethiopia is largely focussed on hydro).
- Some improvements could also be made in **local transport** - contributing to approx. 10% of the eco-burden - by opting for larger trucks in the first steps of the production chain (28 tons instead of 5 tons) and/or using more efficient trucks (EURO 5 instead of EURO 3).
- Unlike commonly expected, the impact of the **use of resin** in industrial bamboo products is definitely not the most significant factor in determining the environmental impact of industrial bamboo products, ranging from 3% (flattened bamboo) to 16% (outdoor SWB) for the carbon footprint and 4% (flattened bamboo) to 21% (outdoor SWB) in terms of eco-costs. A point for improvement could be to increase the amount of formaldehyde free resins such as EPI (Emulsion Poly Isocyanate), because of the relatively low environmental impact (carbon footprint 1,63 kgCO2eq / kg, ecocosts €0,68 / kg) or even switching to a fully biobased resin (EPI is a synthetic resin), with the additional benefit that the industrial bamboo product in that case would have a 100% biobased content.

It is interesting to mention here that the bamboo stem is potentially the most eco-friendly building material available, as it has the unique property that it can be used in construction in its natural form without further processing. However, as shown in for example van der Lugt (2008) the eco-burden of sea transport is calculated with a volume based eco-indicator when the weight/volume ratio is low, which is the case for the bamboo stems, resulting in a carbon footprint for production of 1,369 kg CO2eq/kg stem. However, when the bamboo stem is used locally (China), the sea transport is eradicated and the cradle to gate carbon footprint is only 0,20 kg CO2eq/kg stem.

However, due to the irregularities of the material and the distinct appearance, the market adoption in Western markets of the bamboo stem will be marginal.

A further question is how industrial bamboo materials compare to other commonly used materials, and especially the materials it tries to substitute: tropical hardwood and non-renewable carbon intensive materials such as plastics (e.g. PVC) and metals (e.g. aluminium, steel). In table 7 and figure 16 the carbon footprint is provided for several commonly used materials, including the main bamboo industrial production technologies.

Table 7: Carbon Footprint over life cycle (kgCO2eq / kg or m3 building material) for various common building materials (this report, Idemat 2014 database and Vogtländer et al. 2014)

Carbon footprint (CO2eq per kg product)	**Density** (kg/m3)	**Production** cradle to gate	**End of Life** small elect. power plant (32% efficiency)	**Carbon seq** based on land use change	**Total** / kg	**Total** / m3
Flattened bamboo (d.m. 90%)	850	0,620	-0,704	-0,6370	-0,721	-613
Plybamboo (Caramel) (d.m. 90%)	700	1,018	-0,704	-0,6290	-0,315	-220
SWB indoor (Natural) (d.m. 90%)	1080	0,878	-0,704	-0,6230	-0,449	-484
SWB outdoor (d.m. 90%)	1200	1,193	-0,704	-0,6070	-0,118	-141
Sawn timber, softwood, planed, kiln dried, at plant/RER S (d.m. 90%)	460	0,260	-0,817	-0,1700	-0,727	-334
Idemat2014 Meranti plantation	640	0,710	-0,704	0,000	0,006	4
Idemat2014 PVC (Polyvinylchloride, market mix)	1380	2,104			2,104	2904
Idemat2014 Steel (21% sec = market mix average)	7850	1,838			1,838	14429
Idemat2014 Aluminium trade mix (66% prim 33% sec)	2800	11,580			11,580	32423
Idemat2014 Concrete (reinforced, 40 kg steel per 1000 kg)	2400	0,231			0,231	554

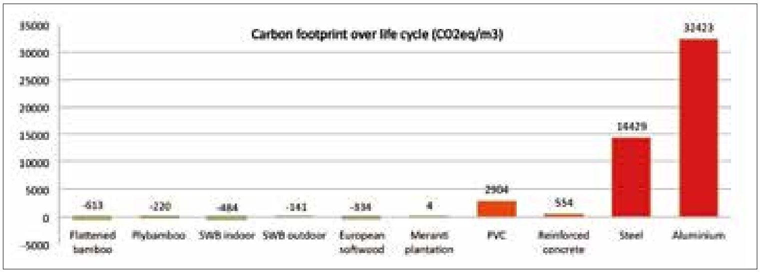

Figure 16: Carbon Footprint over life cycle (kgCO2eq / m3 building material) for various common building materials (this report, Idemat 2014 database and Vogtländer et al. 2014).

Note that tropical hardwood, like Meranti, does not have a carbon sequestration credit. In the best scenario, the carbon sequestration credit is zero, which is the case for plantation wood (currently 35 – 40% of the FSC wood on the market). For other tropical hardwood, the situation is worse: the deforestation of natural rain forests leads to a debit of carbon sequestration, as explained in chapter 3. Note that this debit in LCA is often allocated to the crops which are harvested from that deforested land (e.g., in Brasil). Meranti, however, derives from South East Asia, where the situation is more blurred, and it is not clear how to allocate this carbon sequestration debit. The major disadvantage of hardwood from rain forests, however, is not the carbon sequestration debit, but the negative effect on biodiversity, which is taken into account in the eco-costs for production (cradle to gate) of these materials, see the three scenarios for Meranti (plantation, FSC, natural forest) in the table and graph below.

Table 8: Eco-costs over life cycle (€ / kg or m3 building material) for various common building materials (this report, Idemat 2014 database and Vogtländer et al. 2014)

LCA | Eco-costs (€ per kg product)	Density (kg/m3)	**Production** cradle to gate	**End of Life** small elect. power plant (32% efficiency)	**Carbon seq** based on land use change	**Total** / kg	**Total** / m3
Flattened bamboo (d.m. 90%)	850	0,208	-0,132	-0,086	-0,01	-9
Plybamboo (Caramel) (d.m. 90%)	700	0,285	-0,132	-0,085	0,07	48
SWB indoor (Natural) (d.m. 90%)	1080	0,261	-0,132	-0,084	0,04	48
SWB outdoor (d.m. 90%)	1200	0,356	-0,132	-0,082	0,14	171
Sawn timber, softwood, planed, kiln dried, at plant/RER S (d.m. 90%)	460	0,035	-0.154	-0,023	-0,14	-65
Idemat2014 Meranti plantation	640	0,211	-0,132	0,000	0,08	50
Idemat2014 Meranti FSC	640	2,090	-0,132	0,000	1,96	1253
Idemat2014 Meranti natural forest	640	9,611	-0,132	0,000	9,48	6066
Idemat2014 PVC (Polyvinylchloride, market mix)	1380	0,735			0,73	1014
Idemat2014 Steel (21% sec = market mix average)	7850	0,679			0,68	5329
Idemat2014 Aluminium trade mix (66% prim 33% sec)	2800	4,353			4,35	12190
Idemat2014 Concrete (reinforced, 40 kg steel per 1000 kg)	2400	0,059			0,06	142

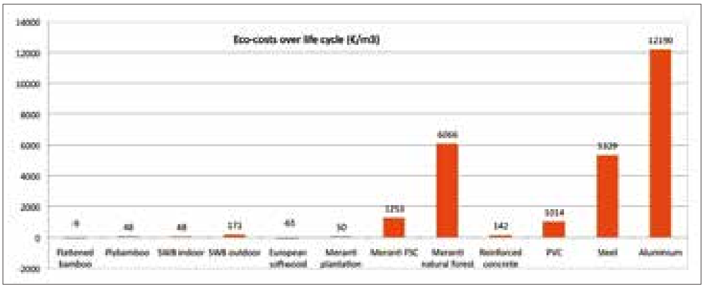

Figure 17: Eco-costs over life cycle (€/ m3 building material) for various common building materials (this report, Idemat 2014 database and Vogtländer et al. 2014).

Although the numbers are per m3 material, and not for a specific application - in which also maintenance and material use based on required mechanical and functional properties are included (functional unit) - these figures do give a good indication how the various materials compare from environmental point of view and can be used as basis for more specific calculations for several applications (functional units).

With respect to their environmental impact, the graphs show that the various industrial bamboo materials are competitive (especially in terms of carbon footprint) with sustainably sourced European softwood, and score slightly better than tropical hardwood from sustainably managed plantations. However, when taking into account that a large portion of tropical hardwood, including FSC certified hardwood[4], still comes from natural forests the differences become larger in the favour of industrial bamboo materials due to loss of biodiversity (included in the eco-costs figures) as well as the carbon sequestration debit (not yet included in the figures above).

In contrast to (tropical) hardwood, one of the main environmental benefits of bamboo, lies at the resource side. As bamboo is a giant grass species, with a fundamentally different way of growing and harvesting than trees, it is less susceptible for clear-cutting / deforestation and

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4 Globally FSC certified tropical hardwood is partly sourced from plantations and semi-natural forests, but the lions share (64%) is still coming from natural forests (harvested with Reduced Impact Harvesting).

very suitable for reforestation for several reasons:

- the mother plant consists of many stems, connected through a vast root (rhizome) system under ground, with new stalks coming up each year;
- it is harvested like an agricultural crop: annual harvest of the 4-5 year old culms provides steady annual income to farmers and even stimulates the bamboo plant to reproduce stems even faster. Note that this is an important difference from wood production where rotation cycles of trees of over 30 years make forests vulnerable for illegal logging / clear-cutting for a short-term gain. As giant bamboo can be harvested annually, it is for this (economic) reason that in practice there is no clear-cutting of giant bamboo forests, as it would mean a waste of capital for the farmer. In fact, much of the bamboo production in the past comes from better forest management[5] (Lou Yiping et al. 2010);
- due to the extensive root system bamboo can be planted in areas where farming is not feasible, e.g., by rehabilitating degraded land - including eroded slopes - and re-establishing functioning and productive ecosystems by improving soil quality and restoring the water table (Kuehl and Lou Yiping 2011). As the growing speed of bamboo is very high (see also point below), it also has a significantly shorter establishment time than wood plantations;
- another important advantage of the bamboo resource is the fast growth resulting in a high annual yield (m3 semi-finished material). This aspect is related to the fact that land might become scarce in the future. For more details about annual yield and establishment times of bamboo plantations is referred to Annex II.

Concluding we can state that at product level the various industrial bamboo products, due to their good mechanical properties (hardness, dimensional stability) and aesthetical looks, perform better than the A-quality (FSC certified) hardwoods it might substitute, both in terms of carbon footprint as well as eco-costs.

When looking from a global perspective at the global carbon cycle (see fig 3 in chapter 3), taking into account the benefits of bamboo at the resource side mentioned above (high yield, annual harvesting, reforestation on degraded land, short establishment time, etc.), it becomes clear that bamboo can be one of the promising solutions in the required shift to a more sustainable, bio-based economy based on renewable resources[6]:

- reducing emissions (and biodiversity loss) caused by deforestation in tropical and sub-tropical areas by providing a viable low emission alternative for tropical hardwood;
- carbon sequestration through reforestation of degraded grassland and slopes with bamboo forests;
- reducing emissions caused by burning of fossil fuels by combustion with heat recovery (production of electricity) at the end-of-life of the increased amount of bamboo products, based on the expected market growth.

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[5] *Although FSC certification is now available for bamboo, the above explains that in reality it is not really required (only increases costs because of increased documentation requirements), as bamboo forests and plantations are managed sustainably for economic reasons.*

[6] *This is a necessity as because of the growth of the global population and the increase of consumption per capita the world's Ecological Footprint is 1,25 times the amount of required resources the Earth can reproduce. See for more information Annex II.*

Annex I Eco-costs

(from Vogtländer J.G., Mestre A., Van der Helm R., Scheepens A., Wever R. (2014))

General

Eco-costs are a measure to express the amount of environmental burden of a product on the basis of prevention of that burden. They are the costs which should be made to reduce the environmental pollution and materials depletion in our world to a level which is in line with the carrying capacity of our earth.

For example: for each 1000 kg CO2 emission, one should invest € 135,- in offshore windmill parks (and the other CO2 reduction systems at that price or less). When this is done consequently, the total CO2 emissions in the world will be reduced by 65% compared to the emissions in 2008. As a result global warming will stabilize. In short: "the eco-costs of 1000kg CO2 are € 135,-".

Similar calculations can be made on the environmental burden of acidification, eutrophication, summer smog, fine dust, eco-toxicity, and the use of metals, rare earth, fossil fuels, water and land (nature). As such, the eco-costs are virtual costs, since they are not yet integrated in the real life costs of current production chains (Life Cycle Costs). The eco-costs should be regarded as hidden obligations.

The eco-costs of a product are the sum of all eco-costs of emissions and use of resources during the life cycle. The widely accepted method to make such a calculation is called Life-cycle Assessment (LCA), which is basically a mass and energy balance, defined in the ISO14040 and ISO 14044.

The practical use of eco-costs is to compare the sustainability of several product types with the same functionality. The advantage of eco-costs is that they are expressed in a standardized monetary value (€) which appears to be easily understood 'by instinct'. Also the calculation is transparent and relatively easy, compared to damage based models which have the disadvantage of extremely complex calculations with subjective weighting of the various aspects contributing to the overall environmental burden.

The system of eco-costs is part of the bigger model of the Ecocosts/Value Ratio.

Background

The eco-costs system was introduced in 1999 in conferences, and published in 2000-2004 in the International Journal of LCA and in the Journal of Cleaner Production. In 2007 the system was updated. It is planned to update the system every 5 years to incorporate the latest developments in science. In the summer of 2012 a new update was released.

The concept of eco-costs has been made operational with general databases, and is described at www.ecocostsvalue.com of the Delft University of Technology.

The method of the eco-costs is based on the sum of the marginal prevention costs (end of pipe as well as system integrated) for toxic emissions related to human health as well as ecosystems, emissions that cause global warming, and resource depletion (metals, rare earth, fossil fuels, water, and land-use). For a visual display of the system see Figure 18.

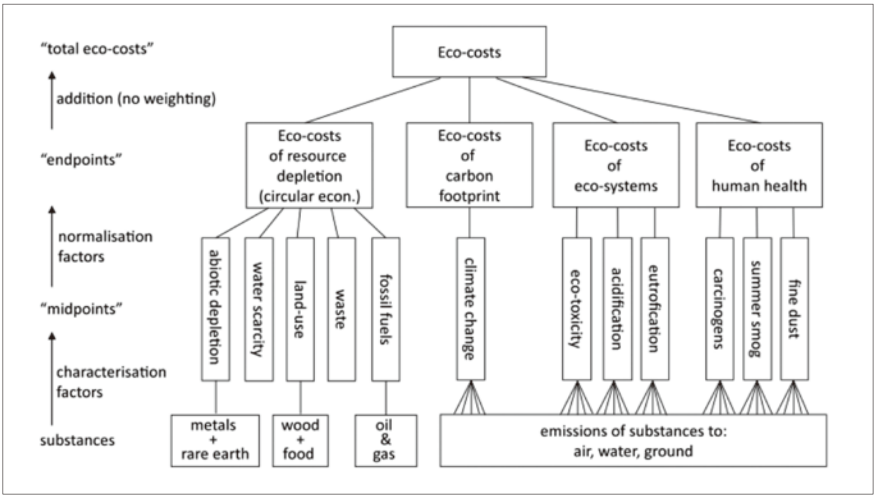

Figure 18: Calculation structure of the eco-costs 2012

Marginal prevention costs of toxic emissions are derived from the so called prevention curve as depicted in Figure 19. The basic idea behind such a curve is that a country (or a group of countries, such as the European Union), must take prevention measures to reduce toxic emissions (more than one measure is required to reach the target). From the point of view of the economy, the cheapest measures (in terms of euro/kg) are taken first.

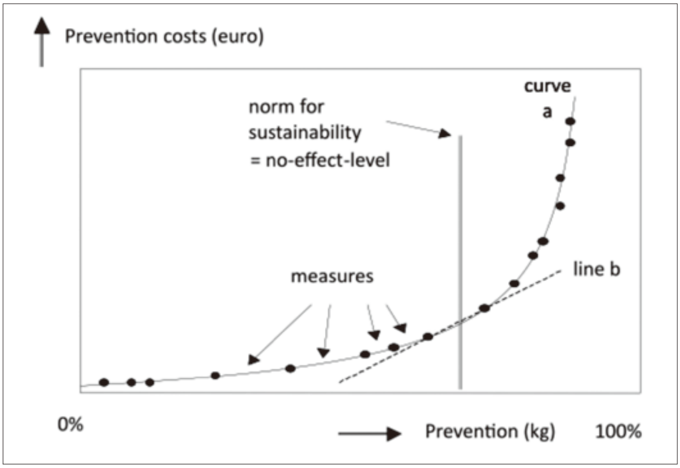

Figure 19: Eco-costs are based on marginal prevention costs at the no-effect-level (the costs in euro/kg of the technical measure).

At a certain point at the curve, the reduction of the emissions is sufficient to bring the concentration of the pollution below the so called no-effect-level. The no-effect-level of CO2 emissions is the level that the emissions and the natural absorption of the earth are in equilibrium again at a maximum temperature rise of 2 degrees Celsius. The no-effect-level of a toxic emission is the level where the concentration in nature is well below the toxicity threshold (most natural toxic substances have a toxicity threshold, below which they might even have a beneficial effect), or below the background level. For human toxicity the 'no-observed-adverse-effect level' is used. The eco-costs are the marginal prevention costs of the last measure of the prevention curve to reach the no-effect-level. See the abovementioned references (Vogtländer et al 2010a) for a full description of the calculation method (note that in the calculation 'classes' of emissions with the same 'midpoint' are combined, as explained below).

The classical way to calculate a 'single indicator' in LCA is based on the damage of the emissions. Pollutants are grouped in 'classes', multiplied by a 'characterization' factor to account for their relative importance within a class, and totalized to the level of their 'midpoint' effect (global warming, acidification, nutrification, etc.). The classical problem is then to determine the relative importance of each midpoint effect. This is done by 'normalization' (= comparison with the pollution in a country or a region) and 'weighting' (= giving each midpoint a weight, to take the relative importance into account) by an expert panel.

The calculation of the eco-costs is based on classification and characterization tables as well (combining tables from IPCC, the UseTox model, tables of ReCiPe, the ILCD, and RiskPoll), however has a different approach to the normalization and weighting steps. Normalization is done by calculating the marginal prevention costs for a region (i.e., the European Union), as described above. The weighting step is not required in the eco-costs system, since the total result is the sum of the eco-costs of all midpoints. The advantage of such a calculation is that the marginal prevention costs are related to the cost of the most expensive best available technology which is needed to meet the target, and the corresponding level of Tradable Emission Rights which is required in future. Example: For reduction of CO2 emissions to a sustainable level, the marginal prevention costs are the costs of replacement of coal-fired power plants by windmill parks at the sea.

The eco-costs have been calculated for the situation in the European Union. It might be argued that the eco-costs are also an indication of the marginal prevention costs for other parts of the globe, under the condition of a level playing field for production companies.

Eco-costs 2012

The method of the eco-costs 2012 (version 2.00) comprises tables of over 3000 emissions, and has been made operational by special database for Simapro, based on LCIs from Ecoinvent v3 and Idemat 2012 (over 9000 materials and processes), and a database for CES (Cambridge Engineering Selector). Excel look-up tables are provided at www.ecocostsvalue.com.

For emissions of toxic substances, the following set of multipliers (marginal prevention costs) is used in the eco-costs 2012 system:

eco-costs of acidification	8,25 €/kg SOx equivalent
eco-costs of eutrophication	3,90 €/kg phosphate equivalent
eco-costs of ecotoxicity	55,0 €/kg Zn equivalent
eco-costs of human toxicity	36,0 €/kg Benzo(a)pyrene equivalent
eco-costs of summer smog (respiratory diseases)	9,70 €/kg C2H4 equivalent
eco-costs of fine dust	34,0 €/kg fine dust PM2.5
eco-costs of global warming (GWP 100)	0,135 €/kg CO2 equivalent

The characterization ('midpoint') tables which are applied in the eco-costs 2012 system, are recommended by the ILCD:

- IPPC 2007, 100 years, for greenhouse gasses
- USETOX, for human toxicity (carcinogens), and ecotoxicity
- RECIPE, for eutrophication, and photochemical oxidant formation (summer smog)
- ILCD, for acidification
- RiskPoll, for fine dust.

In addition to the abovementioned eco-costs for emissions, there is a set of eco-costs to characterize the 'midpoints' of resource depletion:

- eco-costs of abiotic depletion (metals, including rare earth, and fossil fuels)
- eco-costs of land-use change (based on loss of biodiversity, e.g. used for eco-costs of tropical hardwood)
- eco-costs of water (based on the midpoint Water Stress Indicator - WSI - of countries)
- eco-costs of landfills.

The abovementioned marginal prevention costs at midpoint level can be combined to 'endpoints' in three groups, plus global warming as a separate group:

eco-costs of human health	= the sum of carcinogens, summer smog, fine dust
eco-costs of ecosystems	= the sum of acidification, eutrophication, ecotoxicity
eco-costs of resource depletion	= the sum of abiotic depletion, land-use, water, and land-fill
eco-costs of global warming	= the sum of CO_2 and other greenhouse gases (the GWP 100 table)
total eco-costs	= the sum of human health, ecosystems, resource depletion and global warming

Since the endpoints have the same monetary unit (e.g. euro, dollar), they are added up to the total eco-costs without applying a 'subjective' weighting system. This is an advantage of the eco-costs system (see also ISO 14044 section 4.4.3.4 and 4.4.5). So called 'double counting' (ISO 14044 section 4.4.2.2.3) is avoided in the eco-costs system.

The eco-costs of global warming (also called eco-costs of carbon footprint) can be used as an indicator for the carbon footprint. The eco-costs of resource depletion can be regarded as an indicator for 'circularity' in the theory of the circular economy. However, it is advised to include human toxicity and eco-toxicity, and include the eco-costs of global warming in the calculations on the circular economy as well. The eco-costs of global warming are required to reveal the difference between fossil-based products and bio-based products, since biogenic CO_2 is not counted in LCA (biogenic CO_2 is part of the natural recycle loop in the biosphere). Therefore, total eco-costs can be regarded as a robust indicator for cradle-to-cradle calculations in LCA for products and services in the theory of the circular economy. Since the economic viability of a business model is also an important aspect of the circular economy, the added value of a product-service system should be part of the analysis. This requires the two dimensional approach of Eco-efficient Value Creation as described at the Wikipedia page on the model of the Ecocosts/Value Ratio, EVR.

The Delft University of Technology is working on a Version 3.00 of the eco-costs 2012. In this version, metrics on social aspects of the production chain will be added. Aspects are the low minimum wages in developing countries (the "wage deficit"), the aspect of "child labor and extreme poverty", and the aspect of "OSH (Occupational Safety and Health)".

Prevention costs versus damage costs

Prevention measures will decrease the costs of the damage, related to environmental pollution (e.g. damage costs related to human health problems in terms of QALYs). The savings which are a result of the prevention measures are of the same order of magnitude as the costs of prevention. So the total effect of prevention measures on our society is that it results in a better environment at virtually no extra costs, since costs of prevention and costs of savings will level out.

Discussion

There are many “single indicators” for LCA. Basically they fall in three categories:

- single issue
- damage based
- prevention based

The best known “single issue” indicator is the carbon footprint: the total emissions of kg CO2, or kg CO2 equivalent (taking methane and some other greenhouse gasses into account as well). The advantage of a single issue indicator is that its calculation is simple and transparent, without any complex assumptions. It is easy to communicate to the public, as well. The disadvantage is that it ignores the problems caused by other pollutants, and it is not suitable for cradle to cradle calculations (because materials depletion is not taken into account).

The most common single indicators are damage based. This stems from the period of the 1990s, when LCA was developed to make people aware of the damage of production and consumption. The advantage of damage based single indicators is, that they make people aware of the fact that they should consume less, and make companies aware that they should produce cleaner. The disadvantage is that these damage based systems are very complex, not transparent for others than who make the computer calculations, need many assumptions, and suffer from the subjective weighting procedure at the end. Communication of the result is not easy, since the result is expressed in “points” (attempts to express the results in money were never very successful, because of methodological flaws).

Prevention based indicators, like the system of the eco-costs, are relatively new. The advantage, in comparison to the damage based systems, is that the calculations are relatively easy and transparent, and that the results can be explained in terms of money and in measures to be taken. The system is focused on the decision taking processes of architects, business people, designers and engineers. The disadvantage is that the system is not focused on the fact that people should consume less.

Four operational databases

In line with the policy of the Delft University of Technology to bring LCA calculations within reach of everybody, open access databases are made available.

To support Fast Track LCA calculations, excel tables are available on the Internet. These excel tables contain the eco-costs data only (the total as well as the midpoints), since the underlying LCI data are protected with copyright (of Ecoinvent).

Experts on LCA who want to use the eco-costs as a single indicator, can download the full database for Simapro (the Eco-costs Method as well as the Idemat LCIs), free of charge, provided that they have licences for the Simapro software and for Ecoinvent LCIs.

Engineers, designers and architects can have databases, free of charge, for CES and ArchiCAD software, provided that they have a licence for the software.
So, the following databases are available:

- excel tables on the website www.ecocostsvalue.com, tab data (for designers, engineer, architects, business managers, and students, to be used for the Fast Track LCA calculations):
    - a table with data on emissions and materials depletion (more than 3000 substances)
    - a table on products and processes, based on Ecoinvent LCIs and Idemat LCIs[7] (more than 5000 lines)
- an import Simapro database for the method and an import database for Idemat LCIs (software for LCA specialists, only available for Ecoinvent licence holders)
- a database for Cambridge Engineering Selector, Level 2 (software for designers and engineers, available via www.grantadesign.com)
- a dataset for ArchiCAD (3D-BIM software for architects, available via www.kubusinfo.nl)

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7 The Idemat LCIs are based the Ecoinvent LCIs. The reasons to make this extra set of LCIs were:
- extra LCIs of alloys (frequently used by designers and engineers)
- a correction of the "market mix" data of metals (Ecoinvent data are outdated)
- extra LCIs of wood types (softwood types as well as hardwood types)
- a specific selection of LCIs for electricity, heat and transport
- extra LCIs of End of Life (combustion, waste incineration, recycling)
- the Danish food LCIs based on Ecoinvent (instead of ETH data)
- eliminate double counting (of CO_2 and fossil fuels) of electricity in eco-costs

Annex II
Yield of land and social issues

Land-use

Yield of land is a specific aspect of sustainability, related with the fact that land is becoming scarce, especially when current materials (metals, fossil fuels) will be replaced by renewable materials like wood and non-wood forest products like bamboo. This is the notion that the consumption of people is to be supported by the production of land: more consumption leads to less nature. See Fig. 20.

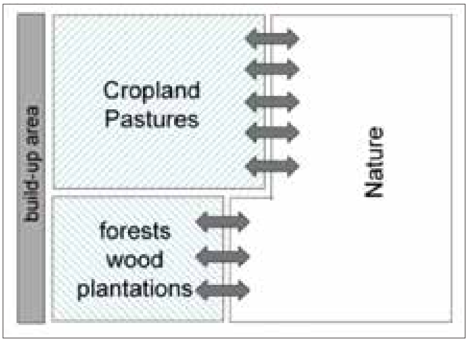

Figure 20: The yield of land must be as high as possible to achieve a minimum ecological footprint

A useful indicator for the scarcity of land is the Ecological Footprint, which is defined as "a measure of how much biologically productive land and water an individual, population or activity requires to produce all the resources it consumes and to absorb the waste it generates using prevailing technology and resource management practices" (WWF 2006).

In 2003 the Ecological Footprint was 14.1 billion global hectares, whereas the global productive area is 11.2 billion hectares. This means that man is currently consuming more than 1.25 times the amount of resources the earth can produce according to this calculation method. So, renewable materials with a high yield of land are required.

Bamboo seems to be a good solution:

- it can grow in areas which are non-productive at this moment (e.g., eroded slopes)
- it is a fast-growing material (it has a high yield)
- its root structure stays intact after harvesting, generating new shoots.

The calculations below for both wood and bamboo are based on numbers for average plantation sites and processing facilities. Note that, depending on geographical and climatic circumstances (e.g. soil, precipitation, elevation, etc.), yields may be considerably higher or lower, so data is only meant to be indicative of the average yields of the specific species in question.

The annual yields have been calculated for the giant bamboo species "Moso" (*Phyllostachus Pubescens*) from China, and "Guadua" (*Guadua Angustifolia*) from Latin America. Guadua is bigger than Moso. It may reach heights up to 20-25 meters and diameters up to 22 cm. Like most bamboos, it reaches its final height in the first half year of its growth, and will come to maturity in the following 4-5 years.

Guadua, like other tropical bamboo types, has a higher yield (approx. a factor 2) than Moso from the Chinese subtropical area of Zhejiang. However, the biodiversity of areas where Guadua grow (Colombia, Ecuador) is a factor 2,5 higher than the biodiversity of the Zhejiang area. Therefore, from the point of view of saving nature, it seems wiser to expand Moso plantations rather than Guadua plantations for future demand of bamboo products (unless the reforestation with Guadua takes place on degraded land, e.g., deforested areas in Brasil).

The maximum annual yield of bamboo and wood may differ depending on the kind of semi-finished materials produced. Calculations have been made in van der Lugt (2008) on three scenarios (qualities), depicted in Fig. 21:

A. High value products (sawn timber, veneer, plybamboo, Strand Woven bamboo, taped mats)
B. Medium value products (MDF, chipboard)
C. For combustion as an energy source and for pulp e.g., for paper production (bamboo compared with eucalyptus).

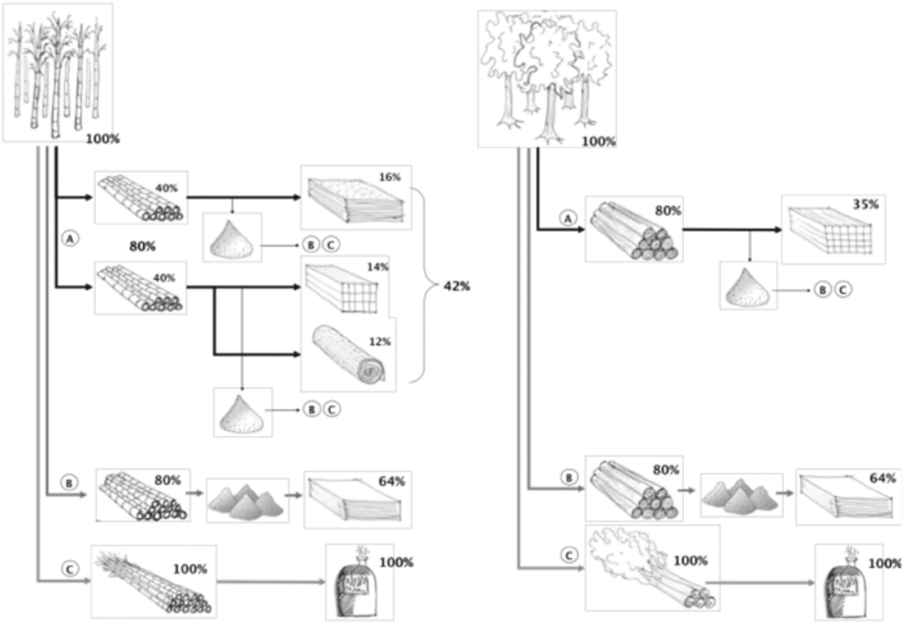

Figure 21: Efficiency during the conversion of bamboo (left) and wood (right) resources to semi-finished materials for 3 scenarios, A-quality, B-quality and C-quality; all percentages related to harvestable standing volume (100%), taken from van der Lugt (2008).

The comparison of the A-quality scenario is made between bamboo, the hardwood species Teak and European Oak and the softwood species Scandinavian Scots Pine, North American Western Red Cedar and Eucalyptus, see figure 22. For detailed calculations about the annual yield of the various bamboo products is referred to section 5.2.2 in van der Lugt (2008). In this INBAR Technical Report flattened bamboo is included following the SWB calculation in table 5.22 of van der Lugt (2008) but with a higher processing efficiency of 90% as there is hardly any waste during processing this product (the stem is the final product in flattened form).

Figure 22 shows that industrial bamboo materials have a larger annual yield than hardwoods (where they compete with in terms of material properties), especially in the case of production of SWB and/or flattened bamboo because of the higher processing efficiency, and even more so in the case of giant bamboo species such as Guadua (annual yield almost twice as high as Moso). Compared to one of the fastest growing wood species worldwide, Eucalyptus, the industrial bamboo products are competitive or even outperform Eucalyptus depending on the production scenario.

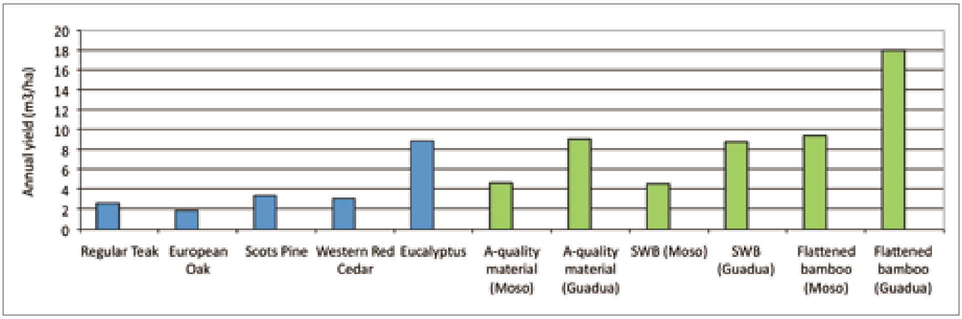

Figure 22: Annual yield for various wood and bamboo species in cubic meters produced per hectare per year (FAO 2006, MAF 2008, van der Lugt 2008, USDA 2013).

A general benefit of bamboo as a reforesting crop compared to wood, is the short establishment time of a bamboo plantation. While the establishment time of a plantation of tropical giant bamboo species such as Moso and Guadua to come to maturity will not take longer than 10 years, the establishment time of a wood plantation to maturity may range from 15 years (Eucalyptus), 30 years (plantation Teak), 70 years (regular Teak) up to 80 years (European Oak). This means that a bamboo plantation will be able to deliver the annual yield of a mature plantation faster than any wood species can.

Note that in case of sustainable harvesting, the root structure stays intact, so the bamboo stems grow from new shoots.

In terms of annual yield of the end product, combined with the biodiversity of the area, it can be concluded that bamboo is one of the best performing renewable resources around, if used as "A-quality" semi-finished material in a durable application (e.g., for housing and use outdoors).

Social aspects

An important sustainability issue of bamboo products is the social aspect of the production system. An advantage of industrial bamboo products is that the value of the product is added locally. Therefore, these industrial bamboo materials can make a good contribution in terms of local employment. A well-managed bamboo industry may combine the three Ps of People, Planet and Profit, from the Triple P Model.

In this Annex, pieces of text are quoted of the publication on bamboo in the Journal of Cleaner Production (Vogtländer et al. 2010b).

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