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Bamboo, a Sustainable Solution for Western Europe Design Cases, LCAs and Land-use

Pablo van der Lugt
Joost Vogtländer
Han Brezet

In partnership for a better world

INBAR

International Network for Bamboo and Rattan

TUDelft

Delft University of Technology

Pablo van der Lugt, PhD
Joost Vogtländer, PhD
Han Brezet, Prof, PhD

The International Network for Bamboo and Rattan (INBAR) is an international organization established by treaty in November 1997, dedicated to improving the social, economic, and environmental benefits of bamboo and rattan. INBAR connects a global network of partners from the government, private, and not-for-profit sectors in over 50 countries to define and implement a global agenda for sustainable development through bamboo and rattan. The mission of INBAR is to improve the well-being of producers and users of bamboo and rattan within the context of a sustainable bamboo and rattan resource base by consolidating, coordinating and supporting strategic and adaptive research and development. INBAR publishes a series of working papers, technical reports, proceedings of conferences and workshops, occasional monographs and newsletters. For more information, please visit: www.inbar.int.
Address: No. 8, East Avenue, Fu Tong Dong Da Jie, Wang Jing, Chaoyang District, Beijing 100102, P.R. China.
Tel: +86-10-6470 6161; Fax: +86-10-6470 2166; E-mail: info@inbar.int

The Design for Sustainability (DfS) Program of the Faculty of Industrial Design Engineering of Delft University of Technology focuses on research in the field of sustainable development. Mass consumption of goods and services should be characterized by continuously improving environmental, economic and social-cultural values. The central objective of the research programme is the exploration, description, understanding and prediction of problems and opportunities to innovate and design products and product service systems with superior quality. For more information please refer to: http://www.io.tudelft.nl/research/dfs
Adress: Delft University of Technology, Faculty of Industrial Design Engineering, Design for Sustainability Program
Landbergstraat 15, 2628 CE Delft, the Netherlands
Tel +31 (0)152782738; Fax +31 (0)152782956; email: dfs-io@tudelft.nl

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Foreword

The need for sustainable development becomes urgently evident. This is caused by our continuously increasing consumption patterns, resulting in a rising pressure on our global resources, and visible through the various financial, food and climate crises around the world. At the supply side, the use of fast growing sustainably produced renewable materials such as bamboo can help to meet this increasing demand.
Life Cycle Assessment (LCA) is used in this INBAR technical report to compare the environmental impact of bamboo materials in Western Europe with commonly used materials such as timber.

This INBAR technical report is an updated version of the environmental assessments made in the PhD thesis "Design Interventions for Stimulating Bamboo Commercialization"[1] by Pablo van der Lugt. The thesis was written as part of the Design for Sustainability Program at the Faculty of Industrial Design Engineering at Delft University of Technology in the Netherlands. The work was supervised by Prof. dr. Han Brezet, while the environmental assessments were executed in close collaboration with Dr. Joost Vogtländer.
The data used in this INBAR Technical Report are slightly modified compared to the eco-costs calculations executed in the PhD thesis. The new data are based on the latest updates of the IDEMAT-2008 and Ecoinvent-V2 databases, from which the eco-costs/kg from the material alternatives have been derived.
Furthermore, some additional modified wood alternatives (Plato® wood and Accoya®) were added to the environmental assessment for the functional unit "terrace decking" in section 2.6.

The report is targeted towards any stakeholder in the bamboo or wood production chain that wants to get a better understanding of the environmental sustainability of bamboo materials compared to alternatives. The environmental assessment also provides insight in the impact of each step in the production process on the overall environmental sustainability of a material. As a result, the supplier of the bamboo materials assessed, Moso International BV, has improved the production process of several of their bamboo materials (for details see section 2.3).

Chapter 1 sketches the rationale of this research, providing the importance of sustainable development, the impact of materials on the environmental sustainability and the potential of renewable materials - and in particular bamboo - for sustainable development, leading to the objective of this report: to assess the environmental sustainability of bamboo materials in Western Europe compared to alternative materials. Chapter 2 provides the results of the environmental assessment in so called "Eco-costs" based on the negative environmental effects caused during the production of bamboo materials. Since the regenerative power of renewable materials is also an important environmental sustainability criterion which is not included in the LCA-based Eco-costs model, in chapter 3 the annual yield of bamboo materials is compared with several timber alternatives. Chapter 4 combines the results of chapter 2 and 3 to come to an overall conclusion about the environmental sustainability of bamboo materials based on current use in Western Europe, current use in the bamboo producing countries themselves and the future use of bamboo materials. Finally, in chapter 5, several recommendations are provided for further research as well as practical recommendations to the bamboo industry how to improve the environmental sustainability of their materials.

At this particular place I would like to thank director René Zaal of Moso International for the support and transparency in providing accurate production data which facilitated a comprehensive and complete assessment of the various bamboo materials. Furthermore I would like to thank my co-authors Dr. Joost Vogtländer and Prof. dr. Han Brezet for their support during my research process as well as in writing this report.
I sincerely hope that this report helps to further increase knowledge amongst stakeholders in the bamboo industry that bamboo materials are not always - as often unfoundedly claimed - the best environmental benign alternative around. This is only the case when several parameters, as presented in this report, are met, which may help shape policy objectives and suggestions for production improvements in the bamboo industry. May this report serve as a stepping stone toward this goal.

Delft, the Netherlands
November 2008
Pablo van der Lugt

[1] Available via http://www.vssd.nl/hlf/m015.htm and most (online) bookstores (ISBN 978-90-5155-047-4), or downloadable via http://www.library.tudelft.nl/ws/search/publications/search/metadata/index.htm?docname=381757

Frequently Used Abbreviations

BMB	Bamboo Mat Board
DUT	Delft University of Technology
FSC	Forest Stewardship Council
FU	Functional Unit
LCA	Life Cycle Assessment
NGO	Non Governmental Organization
NWFP	Non Wood Forest Product
RIL	Reduced Impact Logging
SWB	Strand Woven Bamboo

1 Introduction

1.1 Sustainable Development

Because of the growing human population on our planet in combination with an increase of consumption per capita, more and more pressure is put on global resources, causing the three main interrelated environmental problems: depletion of resources, deterioration of ecosystems and deterioration of human health, and their effects (see table 1.1). Starting in the 1970s through the alarming warning from the Club of Rome, public awareness about the environment has increased drastically over the last decades. In 1987 the World Commission on Environment and Development headed by Brundtland presented the report *Our Common Future* (Brundtland et al. 1987) including the - now widely adopted - concept of sustainable development: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." Although the report also emphasized the importance of decreasing the differences in wealth between developed countries in the "North" and developing countries in the "South", through a better balance in economy and ecology, the term "sustainability" was first mostly interpreted in its environmental meaning.

Table 1.1: The three main environmental problems including their effects (adapted after van den Dobbelsteen 2004)

Note: There is a complex cause and effect relationship between the various problems and the effects; for more information the reader is referred to figure 4.2 in van den Dobbelsteen (2004)

Depletion of resources	Deterioration of ecosystems	Deterioration of human health
Exhaustion of raw materials	Climate change	Ozone at living level
Exhaustion of fossil fuels	Erosion	Summer smog
Exhaustion of food & water	Landscape deterioration	Winter smog
	Desiccation	Noise hindrance
	Ozone layer deterioration	Stench hindrance
	Acidification	Light hindrance
	Nuclear accidents	Indoor pollution
	Eutrofication	Radiation
	Hazardous pollution spread	Spread of dust

Table 1.2: Depletion of resources - consumption and reserves of fossil energy (EIA 2007)

Resource	Fossil fuel reserves left based on most optimistic estimates (production years to go before depletion)
Oil	45 years
Gas	72 years
Coal	252 years

The Brundtland Commission also introduced the factor thinking linked to the idea of sustainable development: to give future generations the same opportunities as mankind has today, present consumption needs to be reduced by a factor of 20 compared to the reference year 1990. This number - which has been largely adopted in environmental policy making - is based on reducing the global environmental burden by half, while anticipating a doubling of the world's population and a five-fold increase of wealth per capita due to increasing consumption especially by emerging economies (van den Dobbelsteen 2004).

Recent targets set by the European Union for the reduction of greenhouse gases are based on a reduction by half the emissions of 1990 in 2050 (and a 20% reduction in 2020).

Although the attention for the environment is improving (e.g. the EU greenhouse emission targets), the factor 20 environmental improvement has not come closer at all. There is a strong debate going on about strategies on the global level, about how to meet these environmental goals (e.g. Cradle to Cradle philosophy by McDonough and Braungart (2002)). However, environmental problems such as climate change have only increased since Brundtland introduced the term sustainable development. This is caused, amongst others, by the increasing globalization, including the more active involvement of new emerging economies such as India and China in the global marketplace. This leads to an increase in wealth and consumption per capita of these densely populated countries.

Most environmental strategies do not yet follow an integrated approach and do not take the three main environmental problems into account in a holistic manner. For example, the acclaimed Cradle to Cradle strategy by McDonough and Braungart (2002) focuses on the re-use of raw materials, but less on energy required during this process (e.g. for recycling and transport).

Due to the increasing globalization, economic and social components were integrated in the term sustainability. These social-economic components are related to human rights, minimization of child labor, health & safety in the workplace, governance and management, transparency and the abolition of corruption and bribery. Although globalization can potentially lead to more equality worldwide, the outsourcing of (production) activities to low income countries has in general led to the opposite, which has driven Non Governmental Organizations (NGOs), pressure groups and governments

in the West to actively put sustainability in its broad form (including the social and economical component) on the agenda, resulting in an increasing emphasis on sustainable consumption and entrepreneurship.
This can be noticed in the adoption of new corporate policies by various multinationals (e.g. Corporate Social Responsibility - CSR), new business models such as the Base of Pyramid approach (Prahalad and Hart 2002), and the increasing establishment of certification schemes for products (e.g. FSC for sustainably produced wood, MSC for sustainable fish, UTZ for sustainable coffee). Companies adopting these policies and certification schemes guarantee that along the complete value chain[2] environmental, social and economical requirements with respect to sustainability are met (OECD 2006). Many cases in the media have shown that especially in the South, in which environmental and social aspects have often never been taken into account previously in business activities, it is very difficult to meet sustainability requirements (e.g. the various reports of production of clothing for the West in sweat shops in Asia).
The social, environmental and economical components of sustainability are usually referred to as "People" (the social component), "Planet" (the environmental component) and "Profit" (the economical component). These three pillars of sustainability are also referred to as "the Triple Bottom Line" (Elkington 1997).
In this INBAR Technical Report, the focus is on the environmental component ("Planet") of sustainability.

1.2 The Impact of Materials on the Environmental Sustainability

The environmental impact of a product depends on all the life cycle stages of the product. Intuitively one expects that the environmental impact of a material has the most influence on the production phase of a product caused by raw material provision and factory production. However, the choice for a specific material in a product also has a strong and direct impact on other aspects of the product in other stages of the life cycle, such as the processing stage (e.g. impact on energy impact and efficiency of production technology), use phase (e.g. durability during life span) and the end-of-life phase (e.g. possibility of recycling, biodegradation, or generation of electricity at the end of the life span). This shows that materials are intrinsically linked to every stage of the life cycle of a product.
If we look at the three main environmental problems introduced in table 1.1, the important role of materials on the environment also becomes evident:

Depletion of Resources

The use of materials contribute to the depletion of resources. Through the extraction of renewable biotic (e.g. timber), finite abiotic (e.g. minerals, oil) raw materials, as well as through the consumption of fossil fuels. It becomes clear that resource depletion is becoming an urgent problem for society. The raw material consumption of industrialized countries per capita is high. It lies in the range of 45-85 tons per year[3] [4] (Adriaanse et al. 1997, Dorsthorst and Kowalczyk 2000), and is expected to grow further (a factor 20, as explaned before) due to the transition of emerging economies (e.g. India, China[5]).
Man is extracting more resources than planet Earth can regenerate. A useful indicator, which makes this deficit quantifiable in numbers, 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 International 2006). The Ecological Footprint also includes global food-, water- and energy production, including the required capacity to absorb the wastes and environmental pollution.
In 2003 the Ecological Footprint was 14.1 billion global hectares, whereas the productive area was 11.2 billion global hectares, which means man is currently consuming more than 1.25 times the amount of resources the earth can produce. With the earlier mentioned population and consumption growth projections, the Ecological Footprint is set to double[6] by 2050 (WWF International 2006). For some time the earth can cover this global "ecological deficit" or "overshoot" by consuming earlier produced stocks. However, when these stocks run out, various resources will become scarce which may result in resource based disasters and conflicts. To bring the Ecological Footprint to a sustainable level, measures should be taken on both the demand and supply side (see figure 1.1). On the demand side the global population, the consumption per capita and the average footprint capacity per unit of consumption (i.e. amount of resources used in the production of

[2] The value chain model was first introduced by Michael Porter (Porter 1985) to analyze the competitive position of a firm in an industry. Since then the model has been widely adopted and further developed over the decades. Kaplinsky (2000) provides the following definition: "The value chain describes the full range of activities which are required to bring a product or service from conception, through the different phases of production (involving a combination of physical transformation and the input of various producer services), delivery to final consumers, and final disposal after use." In each link of the value chain activities are deployed, which require specific knowledge and equipment that add value to the product. Value chains consist of many links that usually represent different companies.
[3] For example, in Japan 14 tons of ore and minerals needs to be mined and processed per capita annually to meet demand for cars and other other metal-intensive products (Adriaanse et al. 1997).
[4] In the building industry in the Netherlands alone, 120 million tons of raw materials are required annually (Dorsthorst and Kowalczyk 2000), of which at least 86% needs to be primary (van den Dobbelsteen 2004).
[5] For example, in China in the coming decade around 400 million new houses need to be built in the countryside, which if built in the traditional brick rural housing type would deplete 25% of China's top soil layer of agricultural land, not even taking into account the enormous amount of coal required for brick production (McDonough and Braungart 2002).
[6] Note that in late studies (Nguyen and Yamamoto 2007) the Ecological Footprint is adjusted to also include consumption of abiotic resources, revealing even larger problems with respect to resource depletion than the original method.

goods and services) determine the total demand of resources. At the supply side the amount of biologically productive area, and the productivity of that area, determine the amount of resources that can be produced globally to meet this demand.

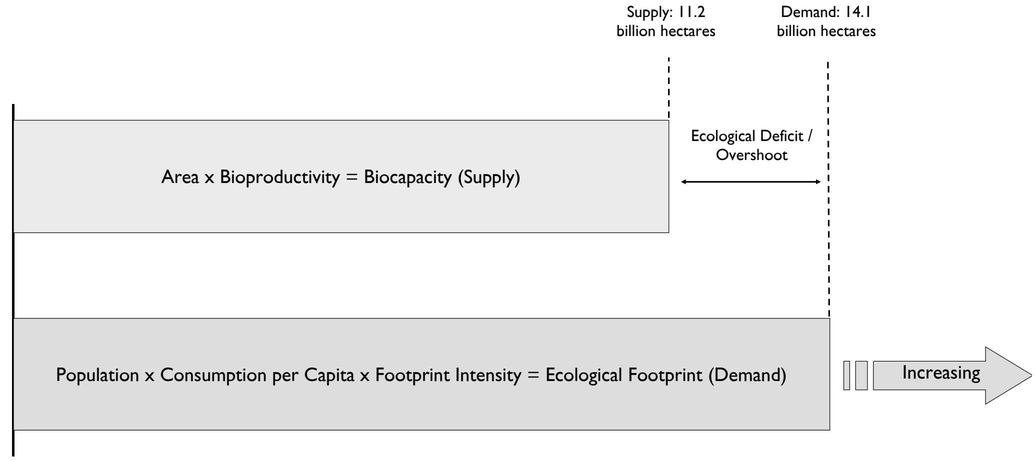

Figure 1.1: Gap between supply and demand between bioproductivity and Ecological Footprint (figure adapted after WWF International 2006)

Ecosystem Deterioration

Next to resource depletion, the high raw material requirements of industrialized countries also impact ecosystems, since these raw materials need to be extracted (e.g. landscape deterioration, erosion), processed and transported (e.g. emissions of greenhouse gases causing climate change), and ultimately disposed of as waste (e.g. toxification, acidification). Depending on the material in question the influence of the extraction and manufacturing of materials on ecosystem deterioration will differ. For example, heavy metals may have a stronger environmental impact during the use and end-of-life phase due to their toxicity and the lack of biological degradability of these materials. Also biotic raw materials such as timber will - in the case of unsustainable management - damage the ecosystem from which the wood is harvested.

Deterioration of Human Health

Some materials, such as the earlier mentioned heavy metals, can be harmful to human health. Also, biotic materials such as timber can be harmful to human health, for example, when they are impregnated with poisonous preservatives (e.g. arsenic, copper, chrome) for a longer life span of the timber.

From the above it becomes clear that directly or indirectly, materials have a large influence on the environmental impact of products, now and in the future. Although the social component of sustainability lies outside the scope of this report, it is important to understand that many raw materials are extracted in developing countries and emerging economies and - in the case of local value addition through processing and product development - yields many opportunities for socio-economic development locally, potentially contributing to sustainable development. However, most value addition to materials still takes place in developed countries (e.g. luxurious products).

1.3 The Potential of Renewable Materials

Above, the important impact of materials on the environmental burden of products was explored. One of the main strategies toward environmental improvement with respect to material use during product development is the deployment of renewable materials. This has also been proposed in the Design for Environment (DfE) strategy wheel (DfE strategy one) by Brezet and van Hemel (1997), and the Three Step Strategy[7] developed by the research group Urban Design and Environment at Delft University of Technology (DUT). Due to the increasing depletion of finite abiotic raw materials, renewable resources are gaining an increasing amount of attention, since they enable the demand for materials in a potentially sustainable manner.
However, besides for input in raw material production, renewable resources may also be used for food or energy production (biomass, biofuel). As a result, the available 11.2 billion global productive hectares compete with each other to produce either food, energy or raw materials, which has led to much controversy worldwide. Using available global hectares for the production of natural crops for biofuels impedes the use of these crops for food (or raw material production), which has resulted in strong upward pressure on food prices worldwide (Worldbank 2008). Furthermore, recent studies (e.g. Searchinger et al. 2008) indicate that in some cases biofuels, stimulated in various governmental policies because of their presumed ability to reduce emission of greenhouse gases, may even increase emission of these gases on the global level, since conversion of forests and grasslands to cropland cause additional emissions. This example shows that renewable

[7] The Three Step Strategy entails the following steps to increase a more conscious use of our resources (Duijvestein 1997):
1. Avoid unnecessary demand for resources
2. Use resources that are unlimited or renewable
3. Use limited resources wisely (cleanly and with a large return)

resources per se are not automatically environmentally sustainable. Global synchronized policies are required, to make sure that the available productive hectares will meet the future global demand for food (and water), energy and raw materials.
For raw material production, wood has always been the best known renewable material. However, because of the high rate of harvesting from available forests worldwide, this renewable resource is under a lot of pressure and with continued unsustainable extraction it can be considered a finite resource as well.
Below, the state of the art of available forest resources is summarized, and the potential of other renewable materials, such as bamboo, is reviewed.

Wood as a Renewable Material

Wood is derived from forests. The total area of forests worldwide is estimated to be just below 4 billion hectares, of which around 0.7-1.3 billion hectares is actively involved in wood production (FAO 2006). For centuries, the total area of forest worldwide has decreased steadily. Although deforestation still continues at an alarmingly high rate of 13 million hectares annually, due to natural expansion, plantation development, and landscape restoration, the net loss of total forest areas in the period from 2000-2005 is "only" 7.3 million hectares per year (almost twice the size of the Netherlands). This means that the net loss of forest area is decreasing compared to the periods before, with a net loss of forest area of 15.6 million hectares annually from 1980-1990 and 8.9 millions of hectares per year from 1990-2000 (FAO 2001, FAO 2006).

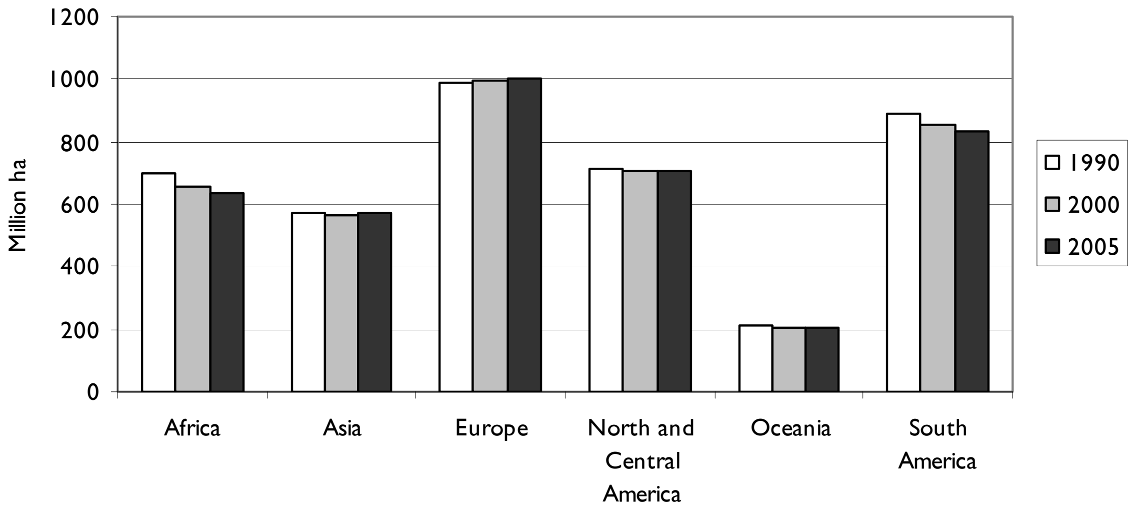

Figure 1.2: Trends in forest area by region[8] 1990-2005 (FAO 2006)

Besides the development of new plantations (+2.8 million hectares per year in 2000-2005), natural expansion, and landscape restorations, another cause of the decrease in net forest loss is the increase of sustainable forest management practices in which the forest from which the wood is derived is kept largely intact. Various schemes exist certifying the sustainability of the chain of custody of wood products. The Program for the Endorsement of Forest Certification schemes (PEFC) and the Forest Stewardship Council (FSC) schemes are most popular in the EU and the USA. The PEFC scheme mostly presumes coniferous wood, whereas FSC has a relatively large share of certified tropical forest. Demand of certified wood is strongly growing, especially in North America and the EU. This is mainly due to the strong lobby of public organizations, NGOs and governments, driven by the growing importance of sustainability. Besides the Planet component, the People and Profit elements of sustainability are also of importance in sustainable forest management certification schemes. The total area of certified forest in 2007 is estimated at just over 300 million hectares (with only 8% in (sub)tropical regions), with a growing rate of approximately 10% annually (Centrum Hout 2007).

[8]FAO (2006) included Northern Asia in the region of Europe (see figure 1.1 on page 8 in the Global Forest Assessment 2005) explaining the high forest area in Europe as a relatively small continent in figure 1.2.

Table 1.3: Certified forest area worldwide per certification scheme, million ha (Centrum Hout 2007)

	2000	2001	2002	2003	2004	2005	2006	2007
FSC	22.17	24.10	31.07	40.42	46.94	68.13	84.29	90.78
PEFC	32.37	41.06	46.31	50.85	54.96	185.16	193.82	196.00
SFI	11.33	22.00	32.37	41.36	45.59	> PEFC	> PEFC	> PEFC
ATFS	-	-	10.50	10.50	10.50	10.50	10.50	10.50
CSA	5.03	5.94	14.44	28.41	47.38	> PEFC	> PEFC	> PEFC
MTCC	-	-	-	-	4.74	4.79	4.73	4.73
Other	-	-	-	-	-	1.18	1.19	1.18
Total	**70.90**	**93.10**	**134.69**	**171.54**	**210.11**	**269.76**	**294.53**	**303.19**

FSC - Forest Stewardship Council; PEFC - Program for the Endorsement of Forest Certification schemes; SFI - Sustainable Forestry Initiative; ATFS - American Tree Farm System; CSA - Canadian Standards Association; MTCC - Malaysian Timber Certification Council. In 2005 SFI and CSA were integrated in the PEFC system

Although the total area of certified forests is growing, the availability of certified wood is low. This is because the demand is very high and is expected to remain growing. The result is high prices of certified wood. A global market survey by FSC reported demand exceeding supply by at least 10 million cubic meters of round wood for hardwood (FSC 2005).
FSC wood requires complex logistics and management systems, needed to ensure system integrity.

The Situation in (sub)Tropical Areas

From figures 1.2 and 1.3 (see below) it becomes clear that while the total forest area increases or stabilizes in more temperate regions (North America, Europe, Northern and Central Asia), in tropical regions around the equator in general the forest area still decreases. This is a problem since the forests with the most biodiversity and biomass per hectare are located mostly in this (sub)tropical area (FAO 2006). Deforestation, especially of tropical forests, is therefore also a major contributor to carbon dioxide emissions, accounting for around 20% of total emissions worldwide (Knapen 2007).

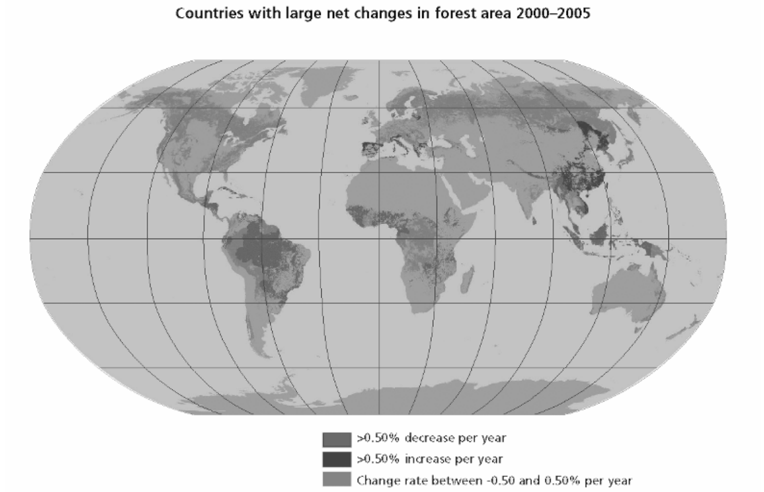

Figure 1.3: Changes in forest area worldwide 2000 - 2005 (FAO 2006)

The causes of tropical deforestation are complex and many. Various studies show that although wood production is an important factor in deforestation, deforestation is mostly caused by slash-and-burn agriculture by poor peasants looking for new ground and fuel wood, permanent agriculture (mainly converting forest in grasslands for cattle breeding) and the development of large civil and infrastructural projects (van Soest 1998). Depending on the region, the importance of these causes may differ. Van Soest (1998) finds that depending on the region, wood production may account for approximately 10-20% of tropical deforestation, while the conversion of forest into agricultural land is perceived as the most important direct cause of tropical deforestation, of which slash-and-burn agriculture and permanent agriculture may account for up to 40% each. The conversion of forest into crop or cattle land is a good example of the Ecological Footprint becoming too large; to fulfil demand for food, man is turning to forest land reserves (required for housing and fuel).
While the total forest area in the (sub) tropics is 858.8 million hectares, only around 15% has a forest management plan, and only 4% is certified (Centrum Hout 2007, ITTO 2004). Around 65% of the total area of certified forest in the tropics falls under the FSC regime (Helpdesk Certified Wood 2008). The largest area of certified forest in the (sub)tropics can be found in Central and South America (12.45 million hectares in January 2008), followed by Asia (5.62 million hectares) and Africa (3.96 million hectares).
About 46% of the total forest area in the (sub)tropics (397.33 million hectares) is used for timber production (plantation and natural forest), of which almost 30% has a forest management plan, and 6.3% is certified (Centrum Hout 2007). Of the total productive area in the (sub)tropics, around 11% (44 million hectares) consists of plantations (FAO 2006) of which 11.1% (4.9 million hectares) is FSC certified (FSC 2008). The combination of the high biodiversity and the high decrease

rate of natural forests in tropical areas, largely explains why environmental groups and governments in the West stress the need for guaranteed sustainable production of tropical timber. However, as mentioned above, supply cannot keep up with demand, especially for slow growing tropical hardwood.

The paragraph above points out that although wood is a renewable material, the sources of this material (forests) are steadily decreasing over time. Especially in tropical regions the total forest area is decreasing rapidly, a.o. due to unsustainable harvesting. The large demand of tropical hardwood because of its good mechanical & aesthetic properties and durability advantages for use outdoors, in combination with the slow growing speed of trees that provide tropical hardwood, makes depletion of especially tropical forests a major problem.

Alternatives for Wood: Non Wood Forest Products

Besides wood there are various other renewable resources that can be used to produce semi finished materials. These renewable materials, such as bamboo, rattan, sisal, cork and reed, fall under the umbrella of the term "Non Wood Forest Products" (NWFP). The Food and Agriculture Organization of the United Nations (FAO) defines NWFPs as "products of biological origin other than wood derived from forests, other wooded land and trees outside forests (FAO 2007). The term encompasses all biological materials other than wood which are extracted from forests for human use, including edible and non-edible plant products, edible and non-edible animal products and medicinal products (e.g. honey, nuts, pharmaceutical plants, oils, resins, nuts, mushrooms, rattan, cork)." Although most NWFPs predominantly have value for local trade, some are important export commodities for international trade. Bamboo and rattan are considered the two most important NWFPs (Belcher 1999).

Still, whereas wood as a renewable material has been mass adopted in Western markets, many other renewable materials belonging to the NWFP-group are not well known and can hardly be found in products in these countries, while some of them could have considerable potential to contribute toward sustainable development, both in the country of production and in the country of consumption. In this report the environmental sustainability of bamboo, as one of these relatively unknown renewable materials, is assessed because of its high potential for regeneration and thus also for raw material production.

1.4 The Latent Potential of Bamboo

Because of its high growth rate and easy processing, bamboo is a promising renewable resource that could potentially substitute for slow growing hardwood. Bamboo has good mechanical properties, has low costs and is abundantly available in developing countries. Its rapid growth and extensive root network makes bamboo a good carbon fixator, erosion controller and water table preserver. The bamboo plant is an eminent means to start up reforestation, and often has a positive effect on groundwater level and soil improvement through the nutrients in the plant debris.

The greatest advantage of bamboo is undoubtedly its enormous growing speed. Bamboo shoots in tropical countries grow up to 30 meters within six months. The record growth speed measured for a bamboo stem is 1.20 meters per day (Martin 1996), which directly shows the potential of bamboo to substitute slower growing wood species in terms of annual yield.

Due to the high growing speed of bamboo, plantations are expected to be proficient in sequestration of carbon dioxide (CO_2). During their growth, plants convert CO_2 through photosynthesis into plant carbohydrates, and emit oxygen in the process. The carbon makes up approximately half of the biomass (dry weight) of the renewable raw material. There is an ongoing discussion about the question whether the carbon sequestration capacity of bamboo is larger than that of fast-growing softwood trees. In appendix B this topic is further elaborated upon.

As a result of these features, at an environmental level (Planet), bamboo materials are expected to be environmentally friendly.

Besides the many traditional applications for local markets and low end export markets in which bamboo in its natural form (stem) is usually used, a wealth of new bamboo materials became available since the 1990s through industrial processing, such as Plybamboo and Strand Woven Bamboo, which can be used for applications in high end markets in the West as well. In figure 1.4 it can be seen how various kinds of bamboo products relate to each other in terms of production technology on the axis traditional - industrial/advanced (bottom of figure). For more examples of innovative and surprising bamboo applications (e.g. bamboo bikes, bamboo food, and bamboo textile), the reader is referred to van der Lugt (2007).

Figure 1.4: Range of bamboo applications possible, based on traditional and advanced technologies (Larasati 1999)

In this section, the potential of bamboo will be explored for giant bamboo species from (sub)tropical regions suitable for industrial processing.

Industrial Bamboo Materials

Through industrial processing of bamboo virtually anything that can be made from wood can also be developed in industrial bamboo materials. The industrial processing of bamboo and in particular the lamination of bamboo strips into boards (Plybamboo), which is mostly applied in flooring, furniture board, and veneer, started in China in the early 1990s. China is still the leading industrial bamboo producer worldwide and supplies more than 90% of bamboo flooring in Western Europe (van der Lugt and Lobovikov 2008). Besides flooring and board materials, China is also a major producer of woven bamboo mats that can be used, for example, in blinds.

Figure 1.5: Plybamboo is available in various colors and sizes

In the past few years, many innovations in the field of production technology have led to the development of new industrial bamboo materials with different properties and possibilities, such as Bamboo Mat Board (BMB), Strand Woven Bamboo (SWB), Bamboo Particle Board, and various experiments with Bamboo Composites.
BMB is made from thin bamboo strips or slivers woven into mats to which resin has been added. Pressed together under high pressure and high temperature, the mats become extremely hard boards, which during pressing can even be put in molds to be processed into corrugated boards.

Figure 1.6 (left): Coarse woven mats form the building stones for BMB
Figure 1.7 (right): Various kinds of bamboo board material including BMB (right side of picture)

SWB is a new bamboo material made from thin rough bamboo strips that under high pressure are glued in molds into beams. An interesting feature of SWB is that there are no high requirements for input strips which means that, unlike the production of Plybamboo, a large part of the resource can be used, thereby utilizing the high biomass production of bamboo to the maximum (see for more information chapter 3). Due to the compression and addition of resin, SWB has a very high density (approximately 1080 kg/ m3) and hardness, which makes it a material suitable for use in demanding applications (e.g. staircases in department stores). Recently, new higher resin content versions of SWB were developed apt for outside use[9], which could make SWB a suitable alternative for scarce tropical hardwood species such as Bangkirai.

Figure 1.8: Application of SWB in a stairway

Other new industrial bamboo materials such as Bamboo Particle Board and Bamboo Plastic Composites are still in the earlier stages of development. These materials are based on copying existing techniques from the wood industry, and are not yet widely available commercially. For an overview of available industrial bamboo materials, the reader is referred to Appendix 1 in van der Lugt and Otten (2007).

An additional advantage of industrial bamboo materials is that because of the labor-intensive process much value is added. Therefore, industrial bamboo materials can make a greater contribution in terms of employment than the development of products made from the bamboo stem, usually based on handicraft techniques with less value added. The cases of bamboo stem (strong in Planet) and industrial bamboo materials such as Plybamboo (potentially stronger in People and Profit) also provide an excellent example of the conflicting character the various pillars of sustainability (the Triple Bottom line) can have.

Besides the bamboo materials being based on industrial production technologies mentioned above, there is also an array of materials available based on non-industrial technologies. Well known examples of non-industrial bamboo materials are the complete bamboo stem and strips derived from the stem. In the box "Bamboo Stem as a Building Material in the West" in subsection 9.3.3 in the PhD thesis of the first author (van der Lugt 2008, downloadable from the website of INBAR and Delft University of Technology, see link in footnote 1) an introduction about the use of the bamboo stem as a building material can be found. Another material based on a non-industrial technology that can be seen in products in the West is the coiling technique, derived from Vietnam, in which long, thin bamboo slivers are rolled tightly by hand into a mold and then glued together.

[9] The latest durability tests executed by SHR (Wood Research Foundation Netherlands) under the commission of Moso International b.v. have revealed that the outdoor version of SWB (higher resin content) falls in durability class I-II (durable - very durable outdoors), which is on par with the most durable tropical hardwood species such as Teak and Azobé. However, the tests were made in laboratory circumstances and focused on the core material and did not include tests on the resistance of the surface of the material to fungi- and UV degradation, nor on the behavior of the material during use. As a consequence more research is still needed about the suitability and competitiveness of SWB for outdoor use (van der Vegte and Zaal 2008).

Figure 1.9: Coiling is a non industrial processing technique that can create surprising effects; chair design (right) by Jared Huke

Bamboo as an Alternative for Hardwood

In the previous section it was found that an increasing use of renewable raw materials may be necessary to bring down the Ecological Footprint to a sustainable level. However, we also found that at the moment, due to increasing consumption and population numbers, raw material demand is set to increase while supply diminishes. This also applies for timber, as the increasing consumption figures (see table 1.4), and the decreasing forest areas (see previous section), especially for tropical timber, show. Also, since emerging economies started to raise their consumption patterns (e.g. China has raised its tropical hardwood import to 7.6 million m3 in 2003, being by far the world's largest importer of tropical logs), the pressure on timber will continue to grow.

Table 1.4: Consumption figures of primary wood products in the EU in 2004, 1000 m3 (ITTO 2004)

Wood	Total	Growth % 2000-2004
Logs	285,878	+7
Sawn timber	88,994	+6
Plywood	5,694	+0
Veneer	1,753	+15

Due to the expected higher annual yields, and the ability of bamboo plantations to be established on areas of land where trees may not survive (e.g. degraded hill slopes), bamboo may be a promising alternative to help meet the increasing demand in raw materials and timber in particular. Thus bamboo may play an important role at the supply side (area × bioproductivity = biocapacity; see figure 1.1) of the Ecological Footprint, to meet future human needs for fibers and timber used as input for housing, clothing, interior finishing, furniture, household products and other consumer durables.

Figure 1.10: Bamboo can also grow well on steep slopes

Because of the many hard fibers present in bamboo, industrial bamboo materials such as Plybamboo and SWB in general have competitive mechanical and aesthetic properties to hardwood products and better mechanical properties than softwood (coniferous wood), whereas the annual production volumes are expected to be higher because of the high growth rate of bamboo. Generalizing, it seems to come down to the following: Bamboo grows faster than softwood, but has hardwood properties. Since industrial bamboo materials are still priced more or less at the same level as hardwood materials (which is higher than most softwoods), the best bet for bamboo is to initially target the markets in which hardwood is used.

In the light of the increasing demand for raw materials, including timber, and the decreasing forest area worldwide, bamboo based materials can therefore serve as an additional alternative to fill the gap between supply and demand of sustainably produced hardwoods. This may apply to both hardwood from temperate and tropical regions, although as seen above, from an environmental point of view it would be best if bamboo could help to meet the demand in tropical hardwood, especially since tropical forests from which this timber is derived are under pressure. This applies in particular to SWB since most tropical hardwood is used in applications outdoors due to its good durability. However, various tropical hardwood species are also used indoors (e.g. Teak) where Plybamboo may also serve as an alternative. In the future some cheaper industrial bamboo products, such as BMB, might be able to compete with softwood.

Besides the development of products for the local market, export markets in the West offer potential markets, especially for industrially produced bamboo materials. In view of the increasing awareness in the West with regard to the necessity of sustainable consumption, there are plenty of possibilities for bamboo to profit from this trend. Furthermore, once bamboo gains a stronger foothold as a potentially sustainable material to be used for products in the West, more trend-following emerging economies such as India and China might follow and will most likely actually acknowledge bamboo as a high end material as well, instead of perceiving it as poor man's timber. It is for these reasons that this report assesses the environmental impact of the use of bamboo materials in products in the West, and in particular on Western Europe as a consuming region.

1.5 The Environmental Sustainability of Bamboo

As mentioned in the previous section, bamboo is often perceived as being environmentally friendly. There are many qualitative arguments, mainly around the biomass production of bamboo, that justify this positive perception. However, many of the industrially produced bamboo materials (Plybamboo, SWB, etc.) go through many energy intensive production steps, produce a lot of waste and are supplemented with many chemical substances (glue, lacquer, etc.). Although the same applies to many wood based products, it does mean that the perceived environmental sustainability of bamboo materials should be questioned.
Therefore, in this report the environmental sustainability of various bamboo materials is determined based on the three environmental problems introduced in table 1.1 at the "debit" side through calculating their environmental impact or eco-burden (negative environmental effects caused by bamboo materials during their life cycle contributing to the three main environmental problems) using the Eco-costs model developed by Vogtländer (2001), based on Life Cycle Assessment (LCA) methodology, and at the "credit" side (diminishing the environmental problems) through calculating the regenerative power of bamboo (bioproductivity; see figure 1.1) through the annual yield. Combined, the environmental impact (debit) and annual yield (credit) can provide an indication of the environmental sustainability of bamboo materials, although the environmental impact calculated through the eco-costs has a broader range than the annual yield (see table 1.5). Note that the annual yield indirectly has a positive impact on climate change through carbon sequestration (see also appendix B). For an explanation about the relationship between Eco-costs and Ecological Footprint, the reader is referred to Vogtländer (2008).

Table 1.5: Together the eco-costs and annual yield determine to a large extent the environmental sustainability of a material

Main problem	Debit (-)	Credit (+)
Depletion of resources	**Eco-costs** Exhaustion of food & water Exhaustion of energy Exhaustion of raw materials	Exhaustion of food & water Exhaustion of energy **Annual Yield** Exhaustion of raw materials
Deterioration of ecosystems	Climate change Erosion Landscape deterioration Desiccation Ozone layer deterioration Acidification Spread of dust Nuclear accidents Eutrofication Hazardous pollution spread	Climate change Erosion Landscape deterioration Desiccation Ozone layer deterioration Acidification Spread of dust Nuclear accidents Eutrofication Hazardous pollution spread
Deterioration of human health	Ozone at living level Summer smog Winter smog Noise hindrance Stench hindrance Light hindrance Indoor pollution Radiation	Ozone at living level Summer smog Winter smog Noise hindrance Stench hindrance Light hindrance Indoor pollution Radiation

Objective

The main research objective of this report is **to assess the environmental sustainability of various bamboo materials based on use in Western Europe, compared to commonly used material alternatives and in particular timber.**

Scope

This report focuses on the use of bamboo materials made from the most commonly used and industrialized giant bamboo species in China: *Phyllostachys pubescens* (referred to as "Moso" - its local name - in the remainder of this report). Moso is perceived as being one of the bamboo species worldwide with the most commercial potential based on its availability, accessibility and potential for industrialization. Moso bamboo grows abundantly in temperate regions in China, can reach lengths of 10-15 meters and a diameter of 10 centimeters, and is very suitable for industrial processing to develop all kinds of industrial bamboo materials. Since besides Moso there are many other bamboo species (1000-1500 species), the results and findings in this research apply in particular to this species and similar giant bamboo species apt for industrial utilization such as *Guadua spp.* (referred to as "Guadua" in the remainder of this report) and *Dendrocalamus Asper*.

Figure 1.11: Guadua is a giant bamboo which grows in clumps mainly in Latin America which may reach heights up to 25 meters

As was shown in section 1.4, there is a wide array of industrially and non-industrially produced bamboo materials available. The focus in this report is on bamboo materials that are already available in Western Europe, or bamboo materials with potential for the Western European market that are expected to become commercially available on the short to medium term (within ten years): the *stem* as representative for non industrial bamboo materials, and *Plybamboo (board and veneer), Strand Woven Bamboo (SWB), Bamboo Mat Board (BMB) and bamboo composites (fibers)* as representatives for industrial bamboo materials. Other, mostly low-end industrial bamboo materials, such as Bamboo Particle Board, are not deemed competitive yet with wood-based boards in the West on the short to medium term. However, for the long term, if production capacity and availability of these materials are improved, they could also become competitive in the West.

2 Environmental Impact in Eco-costs

2.1 Introduction

Although bamboo materials are marketed (and therefore usually also perceived) as environmentally friendly, few quantitative environmental impact assessments using Life Cycle Assessment (LCA) methodology are available for bamboo. The only available studies known to the authors are a study executed by Dr. Richard Murphy (Murphy et al. 2004) and another study executed by the first author for his MSc thesis (van der Lugt 2003) published in various journals (van der Lugt et al. 2003, van der Lugt et al. 2006). The study by Murphy et al. (2004) focuses on the use of bamboo stems (Guadua) in combination with sand/cement (based on the traditional Baharaque technique) as a structural material for social housing in Colombia compared to a similar house executed in masonry and concrete. The environmental impact of the bamboo house was approximately half the impact of the concrete house. Besides the use of the bamboo stem, the study excluded other (industrial) bamboo materials and was based on local consumption of bamboo.
Another LCA study, based on the TWIN 2002 model, was executed by Pablo van der Lugt. Besides the bamboo stem, the study assessed one version of Plybamboo board (10 mm plain pressed Plybamboo). However, part of the input data in the study was not completely reliable, resulting in the new environmental assessments executed in this report. Below, an introduction will be provided about LCA and the models used in this report to analyze the LCA output data to a single indicator for the environmental impact.

LCA

LCA is the commonly accepted methodology to systematically test the environmental impact of a product, service, or in this case, material. Principally, in an LCA, all environmental effects relating to the three main environmental problems (see table 1.1) occurring during the life cycle of a product or material are analyzed, from the extraction of resources until the end phase of demolition or recycling (from cradle to grave). The LCA-methodology developed by the Centre of Environmental Studies (CML, in Leiden, the Netherlands) was presented in 1992 (Heijungs et al. 1992) and was internationally standardized in the ISO 14040 series.
A basic LCA provides an outcome of different effect scores; a weighing method is not included, and an overall judgment of the environmental impact of products is therefore not possible. Furthermore, a basic LCA is very complicated to understand and communicate, which is the reason why various additional models have been developed to be used in combination with a basic LCA in order to indicate the environmental burden of products through a "single indicator". Models to arrive at a single indicator are always subject to discussion, mainly about the weighing method applied in damage based models, but also about the environmental effects included/excluded as well as allocation issues (van den Dobbelsteen 2002). For an overview of available models the reader is referred to van den Dobbelsteen (2004). At Delft University of Technology either the damage based model Eco-indicator 99, or the prevention based model Eco-costs 2007 are used as single indicator models (Vogtländer 2008). In this report the Eco-costs 2007 model is used to identify the environmental burden of the bamboo materials through a single indicator.

It is important to understand that the outcomes of an LCA based calculation should not be perceived as a final judgement, but only as a rough indicator to describe the environmental impact of a product or material. First of all, LCA is a relatively new methodology which is continuously being improved, based on which new models continue to emerge on the market. Secondly, the factors *time* and *place* are not incorporated into an LCA, which means that any LCA based calculation is full of assumptions and estimations which may differ per calculation. For example, for the factor place, even for exactly the same product or material, production data may differ depending on the country of production (e.g. regulations with regard to emissions of production facilities), or the country of consumption (e.g. transport distance). The production context may also differ, which can be best- or worst practice or something in between (e.g. recycling, waste treatment, incorporated at production site), which can cause differences in environmental impact for exactly the same product. Besides these main reasons even more place related aspects may play a role such as the environmental effects of pollution, e.g. some regions are more prone to acid rain than others (Potting 2000).
Furthermore, the time aspect can play a crucial role; if an LCA is based on older data, it may differ considerably from calculations based on current data, based on newer and more efficient production technologies.
Also, due to the the fact that the factor time is not included, annual yields of land by renewable materials such as timber and bamboo are not taken into account in an LCA, and are therefore calculated separately in this report in chapter 3.
Summarizing: an environmental impact assessment based on LCA is often lacking specific data and only provides a overview of the environmental impact (in terms of emissions and materials depletion) of a product or material.

Eco-costs

Eco-costs is a measure to express the amount of environmental burden on the basis of prevention of that burden. It are the costs which should be made to reduce the environmental pollution and materials depletion in our economy to a level which is in line with the carrying capacity of our earth (de Jonge 2005). As such, the eco-costs are virtual costs, since they are not yet integrated in the real life costs of most production chains (Life Cycle Costs). According to Vogtländer (2008), eco-costs should be perceived as hidden obligations, and should not be confused with external costs which are damage costs and therefore only appropriate for damage based LCA-models. In practice, prevention based- and damage based LCA models seem to give similar results (Vogtländer 2008). The Eco-costs model is based on the sum of the marginal prevention costs during the life cycle of a product (cradle to grave) for toxic emissions, material depletion, energy consumption and conversion of land, and includes labor (the environmental impacts related to aspects such as office heating, electricity and commuting) and depreciation (e.g. vehicles, equipment, premises) related to the production and use of products (de Jonge 2005, Vogtländer 2001). The advantage of eco-costs is that it is expressed in a standardized monetary value which can be easily understood, and may be used in the future for the establishment of the right level of eco-taxes and/or emission rights. Although calculation of the prevention based eco-costs is not easy, the calculation is feasible and transparent 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 (Vogtländer 2001). For further examples of the differences between calculations in prevention- and damage based models the reader is referred to the ecocostsvalue.com website (Vogtländer 2008).

System Boundaries and Data Collection for LCA

Since almost every product or material goes through different production activities with different parameters, it is important to make very clear in any LCA based calculation which aspects are and which aspects are not included in the data used for the calculation. Only if these system boundaries are clear, results can be compared with other LCA based calculations, which are based on similar boundaries. In this subsection the most important assumptions and system boundaries used for this environmental impact assessment are provided, as well as the procedure and sources for data collection and -processing for the assessment.

Points of Departure and Basic Assumptions

The environmental impact assessment was executed for various bamboo materials (Plybamboo in several variations, stem, fibers[10], Strand Woven Bamboo and Bamboo Mat Board). Because the aim of this study is to test the environmental sustainability of bamboo compared to wood and especially tropical hardwood, the bamboo materials were compared to relevant wood species. In the Eco-costs 2007 database, available via www.ecocostsvalue.com, the eco-costs of various materials, including various wood species, are provided. This Eco-costs database provides the single indicators (i.e. eco-costs) derived from Life Cycle Inventory (LCI) databases such as Ecoinvent and IDEMAT. The doctorate thesis of Pablo van der Lugt was based on LCIs of Ecoinvent version 1; this INBAR Techincal Report is based on LCIs of Ecoinvent version 2 (available since December 2007). The IDEMAT database is particularly strong in LCIs of wood. This report uses the IDEMAT2008 data, based on the Ecoinvent version 2 LCIs.

The environmental impact assessment for bamboo was based on a so called "Cradle to Site" scenario, which includes all environmental effects until the point of use of the material (Hammond and Jones 2006). Although this is different from a Cradle to Grave scenario, which includes the use and end-of-life phase of a product or material, it is assumed that there are no major differentiating factors between bamboo and wood in these phases, because of the similar life span and chemical composition (same dump or recycle mechanisms deployed) of both materials in the applications in which bamboo was compared with wood (Functional Unit, see below). Thus, an environmental impact assessment based on a Cradle to Site scenario should suffice to compare the eco-costs of bamboo with wood. The assessment for bamboo was based on their use as a semi finished material (excluding additional finishing such as lacquering) in various applications in the Netherlands. From the production side the calculation was based on the use of bamboo resources (Moso species) derived from sustainably managed plantations[11] in the Anji region (province Zhejiang) in China, for which no primeval forests were recently cut.
Finally, for the comparison of material alternatives in a certain function, a general basis of comparison needs to be determined. This basis is called the "Functional Unit" (ISO 1998, van den Dobbelsteen 2002). For a correct comparison, the Functional Unit (FU) is of vital importance: sizes of the alternatives are determined by their technical and functional requirements. Depending on the application these requirements may differ considerably. For example, for a supporting beam, strength might be the crucial criterion while for a floor, hardness and aesthetics might be the most important requirements that should be met, that determine the amount of material required. In the several sections in this chapter for the calculation of each material the FU will be introduced in detail.

Data Collection and Analysis

Evidently, the key to any LCA based calculation is to acquire reliable data about the production process of the products or materials assessed. For this reason extensive inquiries were made in summer 2007 through questionnaires and telephone interviews with the Mr. René Zaal, director of Moso International BV, and the suppliers of Moso International in China (DMVP and Dasso, Mr. Xia; Hangzhou Dazhuang Floor Co, Ms. Isabel Chen). Furthermore, data used for the LCA

[10] Only assessed in a qualitative manner due to lack of data for a complete LCA.
[11] It should be noted that most Chinese plantations originally used to be natural forests from which other vegetation has been removed. This initial loss of biodiversity is not taken into account in this calculation.

calculation executed by the first author in an earlier study (van der Lugt et al. 2003) based on the TWIN 2002 model, was also used as input for an adjusted calculation for the stem based on production in China instead of in Costa Rica (production region for the earlier LCA study by the first author). During the environmental impact assessment of the bamboo materials for each production- and transport process step the environmental effects were noted (mostly based on energy consumption and addition of chemicals), and translated into eco-costs by the second author of this study, Dr. Joost Vogtländer, architect of the Eco-costs model, who assisted the first author in processing the data. The density used in the calculations for all alternatives was based on Wiselius (Wiselius 2001) and Ashby and Johnson (2002). The outcomes of the eco-costs calculation for the bamboo materials, based on the added sum of all process steps, was compared with the data for various alternatives mostly in wood.

Below, the results of the environmental impact assessments for the various bamboo materials will be presented and compared to various wood based materials. In appendix A all the activities calculated during the production chain (Cradle to Site scenario) are covered for the various bamboo materials in various forms (e.g. carbonized, bleached, etc.), including all the assumptions made during this process, which shows the complexity of the data collection and -analysis procedure during environmental impact assessments.

2.2 Wood Based Materials

The eco-costs per kilogram of various wood species and wood based panels are represented in table 2.1 below. Data was derived from the Eco-costs 2007 database (Vogtländer 2008), which largely derives its data from The Life Cycle Inventories (LCIs) of the Ecoinvent version 2.0 database and IDEMAT 2008 database (DfS 2008). For wood the data is based on production figures of sawn timber in dried state ready for sale in wholesale outlets in the Netherlands, often dried and processed into sawn timber in the Netherlands (based on a Cradle to Site scenario, thus including all processing and transport steps). The eco-costs per kilogram figures for wood from the databases are based on averages of the most commonly used production scenarios of the wood for consumption in the Netherlands. For example, Beech for consumption in the Netherlands is mostly produced in Germany, Belgium and Luxemburg based on which the average transport distance is calculated in the IDEMAT database (DfS 2008). For more details is referred to the online databases at www.ecocostsvalue.com.

Table 2.1: Eco-costs per kilogram of various wood (based) materials

Category	Material/species	Data source	Total Eco-costs (€)/kg, including material depletion[12]
Wood	Scots Pine	Idemat 2008 database	0.05
	European Beech	Idemat 2008 database	0.04
	Walnut	Idemat 2008 database	0.06
	Teak (natural forest; RIL)	Idemat 2008 database	7.67 (7.46)
	Teak (FSC certified)	Idemat 2008 database	1.70 (1.49)
	Teak (plantation)	Idemat 2008 database	0.21
	Poplar	Idemat 2008 database	0.03
	European Oak	Idemat 2008 database	0.04
	Robinia	Idemat 2008 database	0.05
	Azobé (natural forest; RIL)	Idemat 2008 database	3.96 (3.87)
	Azobé (FSC certified)	Idemat 2008 database	0.86 (0.77)
	Azobé (plantation)	Idemat 2008 database	0.09
Wood based board material	Particle board, indoor use	Eco-invent 2.0 database	0.13
	Medium density fibreboard	Eco-invent 2.0 database	0.17
	Fibreboard hard	Eco-invent 2.0 database	0.16
	Plywood, indoor use	Eco-invent 2.0 database	0.23
	Plywood, outdoor use	Eco-invent 2.0 database	0.37
	Note: the wood is dried lumber, four sides sawn and planed, in the Antwerp-Rotterdam-Area. Wood based material is at the gate of the production plant		

From table 2.1 it can be seen that due to material depletion, the differences in eco-costs between the various wood species are considerable. The eco-costs for material depletion are based on degradation of biodiversity, caused by the conversion of land (i.e. the difference in biodiversity before and after the harvest) (Barthlott and Winiger 1998). In the case of a

[12] Contribution of material depletion in brackets; if none mentioned, the material depletion is zero (wood from sustainably managed plantations).

sustainably managed plantation, material depletion is zero because the biodiversity (species richness) remains the same, resulting in zero eco-costs. Since most wood from Europe comes from sustainably managed plantations nowadays, the material depletion for European wood is not much of an issue.
In the case of wood deriving from tropical forests (see for example Teak and Azobé in table 1.1) the situation is different because of the high biodiversity of the source. Teak comes from South East Asia, where the biodiversity is very high (resulting in eco-costs of 13,2 € per m2 of land). Azobé comes from Cameroen, Gabon and Nigeria, where the average biodiversity is also high (resulting in eco-costs of 11,3 € per m2 land).
In the calculations Reduced Impact Logging (RIL) is assumed (Rose 2004), resulting in 50% loss of eco-value in a tropical forest. With a yield of 25 m3 initial harvest per hectare, resulting in 14 m3 dried lumber (four sides sawn and planed beams), the eco-costs of land-use of Azobé is 3,87 €/kg; see table 2.1. Note that the specific gravity is quite different: Teak 630 - 680 kg/m3, Azobé 940 - 1100 kg/m3. For details of this calculation, and calculations of other wood types, see Vogtländer (2008).
As a result, tropical hardwood RIL harvested from a natural forest is not competitive with European grown wood with respect to the eco-costs/kg.

Under the FSC certification scheme, the compensation costs because of material depletion are considerably lower. The FSC certification scheme guarantees - to some extent - a sustainable and socially responsible chain of custody when harvesting, transporting and processing trees into sawn timber. FSC practices, however, differ from country to country; local customs are adhered to.
Less than 40% of FSC wood is harvested from plantations (FSC 2008). The rest is harvested from natural forests. RIL logging is more or less guaranteed, and one may hope that areas with high biodiversity are preserved.
Under the assumption that 40% of FSC wood is logged at plantations, and under the assumption that the higher biodiversity areas are preserved - resulting in 2/3 less degradation of biodiversity - Vogtländer (2008) assumes a 10% loss in eco value caused by harvesting FSC wood (instead of a 50% loss assumed for RIL), corresponding with 0.77 €/kg for Azobé (see table 2.1).

For more details of the impact in eco-costs of all other activities along the production chain based on a Cradle to Site scenario for the various wood species the reader is referred to the IDEMAT2008 data and the excel file Ecocosts Calculations on Wood at www.ecocostsvalue.com tab FAQs, question 1.7.

Note that the eco-costs of wood from plantations are mainly determined by the eco-costs of transport, where the eco-costs of transport by sea is approx. 0.0052 €/tkm, and the eco-costs of transport by road is approx. 0,034 – 0,039 €/tkm.

In the next paragraphs, the eco-costs for the various wood based materials will be compared to the results of the eco-costs for the bamboo based materials for that typical function.

2.3 Plybamboo

Plybamboo materials exist in many sizes, colors, layers and patterns. The most common differences are the thickness, ranging from 0.6 mm (veneer) to 40 mm (5-layer Plybamboo panel), the texture (plain pressed or side pressed) and the color (the most commonly used colors are bleached and carbonized; see figure 2.1).

Figure 2.1: Plybamboo is available in various colors, textures and sizes; in the left picture Plybamboo flooring (from left to right: bleached side pressed, bleached plain pressed and carbonized plain pressed) is depicted, in the right picture a sample of a 3-layer carbonized Plybamboo panel is shown

The environmental impact of 3-layer Plybamboo board (bleached and carbonized), 1-layer Plybamboo board (bleached and carbonized, plain pressed and side pressed) and veneer (bleached and carbonized, plain pressed and side pressed) were calculated. The standard dimensions of most Plybamboo boards are 2440 mm (length) x 1220 mm (width), which was used as a base element for the eco-costs/kg calculations for Plybamboo. In appendix A all the calculated activities during the chain of these Plybamboo materials are presented, including all the assumptions made during this process. The results of these elaborate calculations in appendix A are depicted in the form of the final eco-costs/kg of the various Plybamboo boards in the tables below.

Table 2.2: Eco-costs per kg of 3-layer Plybamboo board

Product	Eco-costs (€)/kg
3-layer bleached Plybamboo board	0.354
3-layer carbonized Plybamboo board	0.395

Table 2.3: Eco-costs per kg of 1-layer Plybamboo board in several variations

Product	Eco-costs (€)/kg
1-layer plain pressed Plybamboo board (bleached)	0.333
1-layer side pressed Plybamboo board (bleached)	0.358
1-layer plain pressed Plybamboo board (carbonized)	0.374
1-layer side pressed Plybamboo board (carbonized)	0.398

Table 2.4: Eco-costs per kg of Plybamboo veneer in several variations

Product	Eco-costs (€)/kg
Plain pressed veneer (bleached)	0.78
Side pressed veneer (bleached)	0.49
Plain pressed veneer (carbonized)	0.88
Side pressed veneer (carbonized)	0.55

Please note that these figures do not say a lot yet. Only when a material is used as an element in a product in which it fulfils a function (the so called Functional Unit, FU), the required amount of kilograms of the material can be calculated, and it can be compared with other materials based on the eco-costs per FU. Depending on the form or density of the material, this may result in completely different outcomes with respect to the eco-costs. For example, while the eco-costs per kilogram of steel at 0.487 €/kg (Vogtländer 2008) is almost as high as for the Plybamboo boards, because of the high density of steel (7850 kg/m3), a lot more kilograms of material will most likely be required (depending on the function). The potentially confusing character of the eco-costs/kg is also the reason why the results for the various Plybamboo materials were represented in separate tables above. Later in this chapter the eco-costs for bamboo materials for several FUs will be compared to other materials.

However, analyzing the production process steps (see appendix A) that have led to the eco-costs/kg figures can already provide insight into the contribution of each process step to the environmental impact for each individual material. This process step analysis can pinpoint causes of the difference in eco-costs/kg for bleached and carbonized Plybamboo material (see figure 2.2), and the difference in side pressed and plain pressed Plybamboo (only applicable for the 1-layer board).

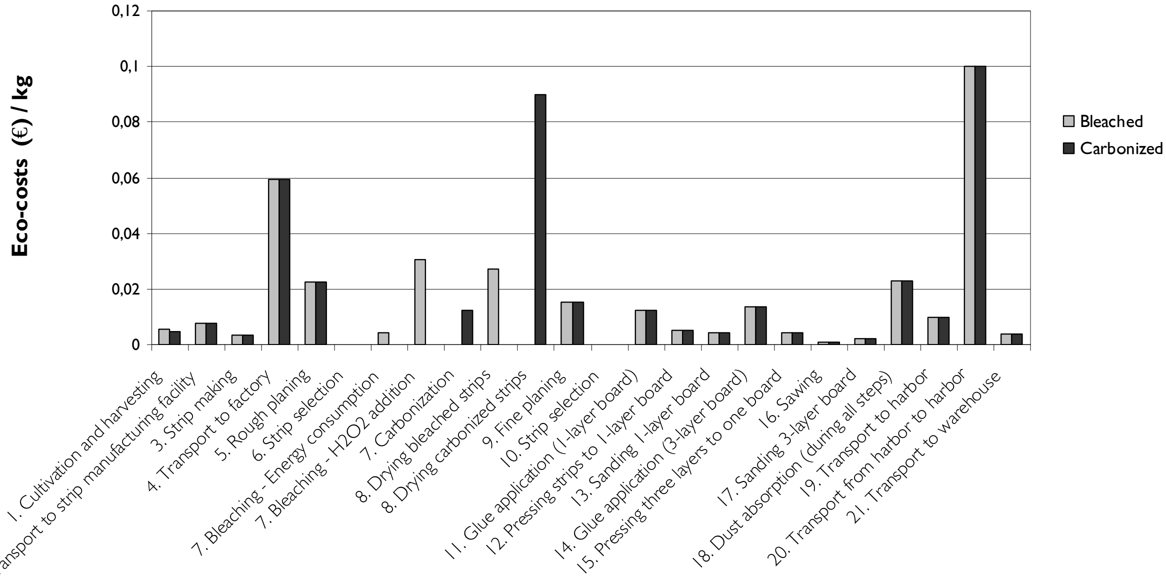

Figure 2.2: Environmental impact in eco-costs (€/kg) of the various process steps during the production and transport of 3-layer Plybamboo board to the Netherlands

From figure 2.2 some conclusions can be drawn. First of all, the figure shows that there are many process steps that bamboo as a resource has to go through until it ends up in the final board material in the warehouse in the Netherlands. Secondly, the figure shows that transport (dispersed over various process steps) has a large influence on the environmental impact of Plybamboo. For precise numbers and percentages of each process step, the reader is referred to the tables in appendix A. Finally, figure 2.2 tells us that the preservation and drying phase also has a relatively large impact on the eco-costs for Plybamboo, and is also the differentiating factor causing the difference in eco-costs per kilogram between the bleached and carbonized version of Plybamboo. Whereas the addition of H_2O_2 has a relatively large impact on the environmental impact of bleached Plybamboo, for carbonized Plybamboo the longer and more drying cycles required (total of 240 hours) levels out the smaller environmental impact carbonization has as a preservation method[13]. Similarly, the differences between plain pressed and side pressed Plybamboo can be assessed, which is differentiating in the case of a 1-layer board (see table 2.3 above), caused by the larger amount of glue required in side pressed bamboo (for details see tables A3-A7 in appendix A).

Based on these kinds of analyses, Plybamboo material producers can see where they should focus their attention if they want to lower the environmental damage the production and transport of their material inflicts, see also footnote 13. This can be done, for example, by finding more environmentally friendly preservatives/chemicals for bleaching, or finding less energy consuming ways to dry carbonized bamboo strips (e.g. solar powered drying chamber; see figure 2.3 for a low-cost example used in Colombia).

Figure 2.3: Low cost solar powered drying chamber for bamboo strips in Colombia developed by Jörg Stamm

[13] It should be noted that, according to the material importer (Moso International), the second drying cycle for carbonization (see also appendix A) is not necessary. As a result, the material producer intends to shorten the drying time, cutting down the eco-costs. This case shows the practical use of LCA for improving the environmental sustainability.

Eco-costs per FU

As mentioned above, the eco-costs/kg figures of Plybamboo do not say a lot compared to other materials; it is only when they are used in a certain application - which determines the required amount of kilograms per material to satisfy needs in this FU - that the eco-costs of materials can be properly compared. Usually a material will be deployed in an application in which the specific advantages of the material can serve as an added value. The competitive advantages of Plybamboo lie in the hardness and aesthetic qualities of the material, which can be utilized in applications such as flooring or tabletops. Compared to most wood based materials in these applications, there will not be many differences in volume used to satisfy needs for the application. Since the initial PhD research of Pablo van de Lugt focused on the interior decoration sector, Plybamboo was compared with various wood materials for a piece of furniture, e.g. in the function of a tabletop (see an example in figure 2.4). Later in this section Plybamboo is compared in a lounge chair with wood alternatives based on its bendability.

<u>Tabletop as FU</u>

Depending on the market segment targeted, different wood based alternatives can be used as tabletop. In general the aesthetic properties are a most important product attribute for wood species selection in this application. Furthermore, wood species are usually used that are sufficiently hard (so deciduous trees like Pine are not eligible), and combine this feature with a warm color and beautiful distribution of rays, such as European Oak, Teak, or Walnut. The size (and especially thickness) of the tabletop will usually be chosen based on dimensions of the semi finished material to facilitate an efficient production. For this particular environmental assessment will be calculated with a dimension of the tabletop of 1220 x 1220 x 20 mm. In the case of medium to high end markets, customers tend to prefer a solid wooden tabletop. To reduce costs in low end markets, producers usually opt for the use of a wood based board, such as MDF, chipboard, hardboard or plywood, as carrier, and a top layer of veneer with nice aesthetic properties as mentioned above (European Oak, Walnut and Teak). Based on these parameters the eco-costs per FU were calculated for both the medium-high end market (based on solid material) and low end market (based on a wood based board material as carrier); see the tables below. For Plybamboo it was calculated with the eco-costs/kg of the 3-layer panel. In the final column the eco-costs/FU of the most environmentally friendly 3-layer panel (bleached) was compared to the various wood alternatives. Note that in the calculation, the life span, maintenance and end-of-life scenario is assumed not to be differentiating for the various alternatives in this application.

Figure 2.4: Plybamboo board used as a tabletop

Table 2.5: Eco-costs per tabletop of 1220 x 1220 x 20 mm (0.0298 m3) based on solid material

Material	Density (kg/m3)	Eco-costs/kg	Kg/FU	Eco-costs (€)/FU	Eco-costs/FU (ratio)
3-layer Plybamboo carbonized	700	0.395	20.9	8.26	112%
3-layer Plybamboo bleached	700	0.354	20.9	7.40	100%
European Oak	700	0.04	20.9	0.84	11%
Walnut	690	0.056	20.5	1.15	14%
Teak (natural forest; RIL)	650	7.67	18.8	144	1950%
Teak (FSC certified)	650	1.70	18.8	32.0	432%
Teak (plantation)	650	0.21	18.8	3.95	53%

The eco-costs/kg numbers for wood relate to sawn timber. The eco-costs/kg for veneer production need to be adjusted, since veneer production has higher material losses due to the thin character of the material. As calculated in appendix A material input during the production of the highest quality (zero defect), bamboo veneer is due to these material losses 1.38 times (side pressed bamboo) to 2.35 times (plain pressed bamboo) higher compared to the 1-layered Plybamboo board. For the production of the highest quality wood veneer it is assumed that material input is twice as high compared to the production of sawn timber, which means that the eco-costs/kg are doubled compared to the eco-costs/kg for sawn timber in table 2.5. To calculate the eco-costs for a tabletop for the low end market based on veneer and an inexpensive wood based board as carrier (see table 2.8), first the eco-costs for the veneer and wood based board are calculated separately (see tables 2.6 and 2.7). For the veneer calculation in the final column, the eco-costs of the various alternatives are compared with the bamboo alternative most often used in practice (side pressed carbonized). For the carrier board calculation and the total tabletop (carrier + veneer) in the final column, the ratio compared to the most environmental friendly bamboo material (3-layer bleached Plybamboo, see table 2.5 above) is depicted.

Table 2.6: Eco-costs per 1220 x 1220 x 0.6 mm (0.00086 m3) veneer sheet used for a tabletop

Material	Density (kg/m3)	Eco-costs/kg	Kg/FU	Eco-costs (€)/FU	Eco-costs/FU (ratio)
Plain pressed veneer (bleached)	700	0.78	0.60	0.47	141%
Side pressed veneer (bleached)	700	0.49	0.60	0.29	88%
Plain pressed veneer (carbonized)	700	0.88	0.60	0.53	159%
Side pressed veneer (carbonized)	700	0.55	0.60	0.34	100%
European Oak	700	0.08	0.60	0.05	15%
Walnut	690	0.112	0.59	0.066	19%
Teak (natural forest; RIL)	650	15.3	0.56	8.5	2500%
Teak (FSC certified)	650	3.4	0.56	1.9	558%
Teak (plantation)	650	0.42	0.56	0.24	71%

Table 2.7: Eco-costs per 1220 x 1220 x 20 mm (0.0298 m3) of wood based board material used as carrier in a tabletop

Material	Density (kg/m3)	Eco-costs/kg	Kg/FU	Eco-costs (€)/FU	Eco-costs/FU (ratio)
MDF	750	0.17	22.35	3.80	51%
Plywood (Indoor)	600	0.23	17.9	4.12	56%

Table 2.8: Eco-costs per tabletop consisting of a 1220 x 1220 x 20 mm carrier finished with veneer (accumulation of tables 2.6 and 2.7)

Material (carrier + veneer)	Eco-costs (€)/FU	Eco-costs/FU (ratio)
MDF + Plain pressed veneer (bleached)	4.27	58%
MDF + Side pressed veneer (bleached)	4.09	55%
MDF + Plain pressed veneer (carbonized)	4.33	59%
MDF + Side pressed veneer (carbonized)	4.14	56%
MDF + European Oak	3.85	52%
MDF + Walnut	3.87	52%
MDF + Teak (natural forest; RIL)	12.3	166%
MDF + Teak (FSC certified)	5.7	77%
MDF + Teak (plantation)	4.04	55%
Plywood + Plain pressed veneer (bleached)	4.59	62%
Plywood + Side pressed veneer (bleached)	4.41	60%
Plywood + Plain pressed veneer (carbonized)	4.65	63%
Plywood + Side pressed veneer (carbonized)	4.46	60%
Plywood + European Oak	4.17	56%
Plywood + Walnut	4.19	56%
Plywood + Teak (natural forest; RIL)	12.6	170%
Plywood + Teak (FSC certified)	6.0	81%
Plywood + Teak (plantation)	4.36	59%

In figure 2.5 the results of table 2.5 (solid material) and table 2.8 (veneer on carrier) are visually represented. In the figure alternatives based on a wood based board material and a veneer carrier (low end market) are depicted in black, while the solid wood alternatives are depicted in gray and the solid bamboo alternatives in light gray.

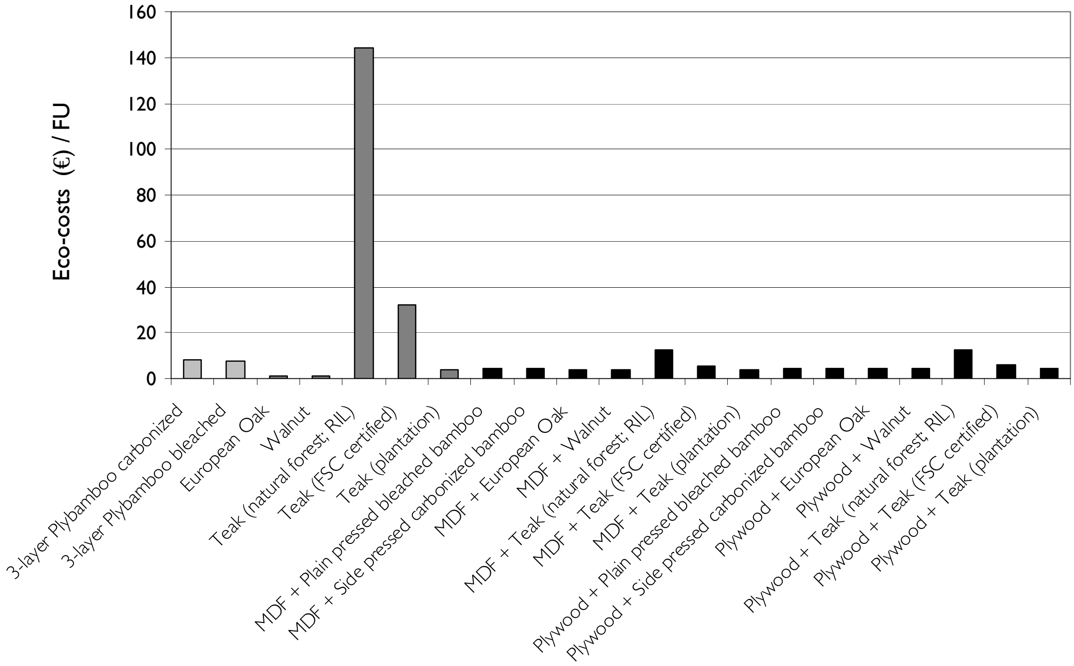

Figure 2.5: Eco-costs for a 1220 x 1220 x 20 mm tabletop for various wood- or bamboo based alternatives (including alternatives harvested in natural forests)

From figure 2.5 it becomes immediately clear that from an environmental point of view the use of tropical hardwood, even FSC, has a very large environmental burden, and should preferably be avoided. Since the bamboo assessed in this evaluation was derived from a sustainably managed plantation, it is fair for the comparison with wood to focus on the eco-costs figures for wood also sourced from a sustainably managed plantation. To better understand nuances between alternatives sourced from sustainably managed plantations, the environmental costs of alternatives from FSC certified Teak and Teak from natural forests were excluded in the graph below (see figure 2.6).

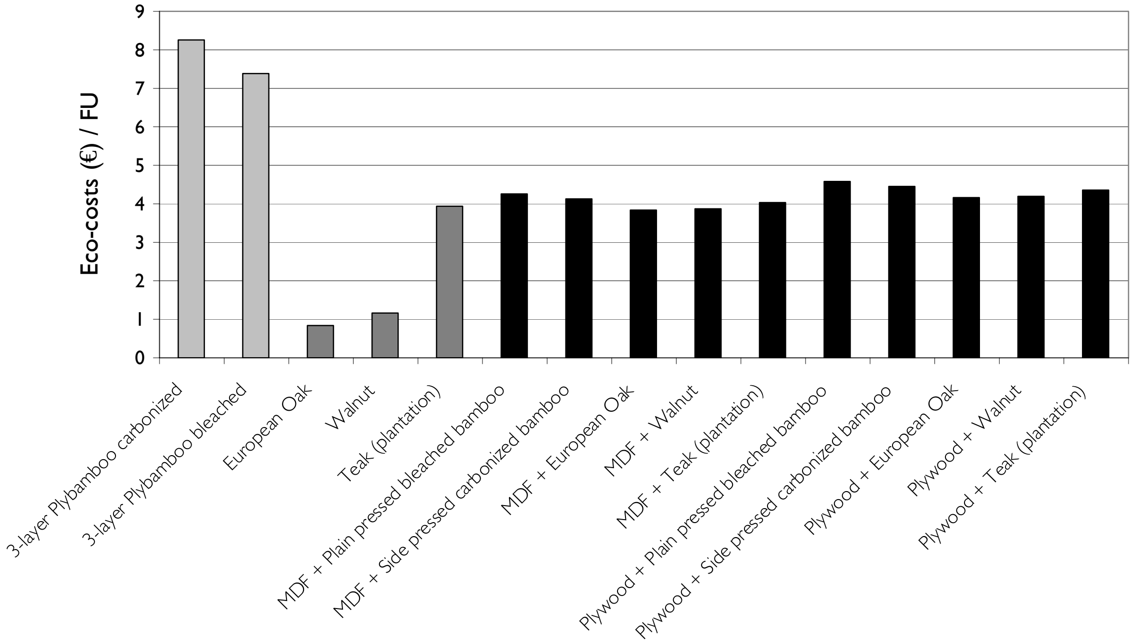

Figure 2.6: Eco-costs for a 1220 x 1220 x 20 mm tabletop for various wood- or bamboo based alternatives (excluding alternatives harvested in natural forests)

Several conclusions can be drawn from figure 2.6.

First of all, it can be seen that tabletops, made from solid wood which is grown and harvested in the same continent as where it is used (Walnut, European Oak), have by far the lowest environmental burden (14% respectively 11% compared

to 3-layer bleached Plybamboo, see table 2.5). If this solid wood is derived from other continents far away, as in the case of plantation grown Teak from South-East Asia & Brazil, the environmental impact is higher than for the other alternatives (excluding Plybamboo). If MDF is chosen as carrier, the environmental impact is three times as high as for solid wood grown in Europe, but still more than twice as low as for the 3-layer Plybamboo alternatives. If Plywood is chosen as carrier, the situation is similar.
Figure 2.6 shows that, in terms of eco-costs, it is better to use bamboo veneer on a wood based board as carrier, than Plybamboo in solid form[14].

To better understand the differences in eco-costs between the various alternatives one should analyze and compare the environmental impact of the various production process steps for bamboo (see figure 2.2 for Plybamboo) and for wood (see the IDEMAT database (DfS 2008)). In figure 2.2 it was found that for Plybamboo, transport and drying (carbonized version) or bleaching through H_2O_2 & drying (bleached version) contributed most to the eco-costs. Depending on the species and location of sourcing for various wood species, material depletion (especially from natural tropical forests; see above), transport and drying are the process steps which are most harmful in terms of eco-costs for wood.

It should be noted that sea transport from China to the Netherlands has a large impact (25-28%; see tables A1 and A2 in appendix A) on the environmental burden of Plybamboo. If Plybamboo is used locally (in China) the eco-costs will therefore be considerably lower, and Plybamboo might become increasingly competitive in terms of eco-costs with locally grown wood species.

<u>Lounge Chair as FU</u>
During the design project "Dutch Design meets Bamboo" (for more info see van der Lugt 2007), it was found that the bendability can also be acknowledged as a competitive advantage for Plybamboo (see for example lounge chair designed by Tejo Remy and René Veenhuizen in figure 2.7). Therefore, this chair was chosen as another FU to compare the eco-costs of bamboo with wood.

Figure 2.7: Bamboo chair by Tejo Remy and René Veenhuizen

The chair consists of seven slabs of 1-layer carbonized, side pressed Plybamboo (three slabs of approximately 2.25 × 0.15 × 0.005 m, four slabs of 1.25 × 0.15 × 0.005 m; in total 0.0088 m3 of material). For bending, Beech is usually chosen as the most appropriate wood species. As an additional alternative plywood topped with a veneer layer of an aesthetic wood species (e.g. Walnut) may be used in this application. For both the Beech and plywood alternatives it is assumed that the same volume of material is required as for Plybamboo. In table 2.9 and figure 2.8 the eco-costs/FU for Plybamboo and the various alternatives are represented.

Table 2.9: Eco-costs per year for 1-layer Plybamboo (carbonized) and wood alternatives used in the bended lounge chair

Material	Density (kg/m3)	Eco-costs/kg	Kg/FU	Eco-costs (€)/FU	Eco-costs/FU (ratio)
1-layer Plybamboo carbonized	700	0.398	6.16	2.45	100%
European Beech	670	0.037	5.90	0.22	8.9%
Plywood (local wood, excluding veneer layer)	600	0.23	5.28	1.21	49%

[14] Please note that additional eco-costs of adhesives required to glue the veneer onto the wood based carrier were not taken into account in this calculation.

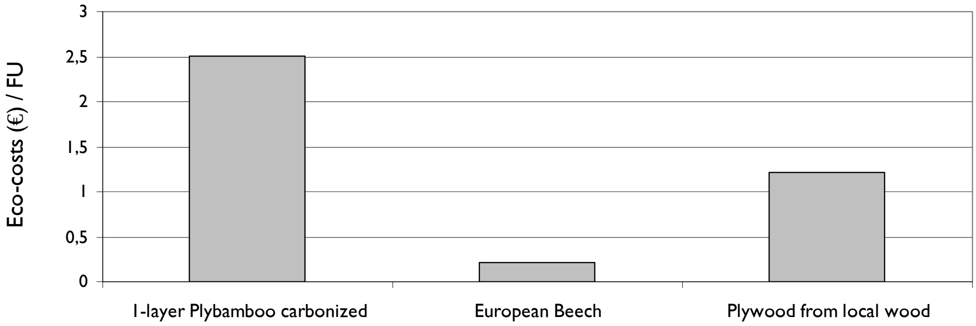

Figure 2.8: Eco-costs per year for 1-layer Plybamboo and wood alternatives used in the bended lounge chair

From figure 2.8 it becomes clear that also in this application the Plybamboo alternative scores worse in terms of eco-costs compared to relevant wood alternatives for this particular application. Here also applies that the eco-costs for Plybamboo will be lower if it is not exported and sea transport eco-costs can be avoided (24.9% for carbonized side-pressed 1-layer Plybamboo board; see table A6 in appendix A).

2.4 Stem

Figure 2.9: Bamboo stem of the Moso species

The bamboo stem, used as input for the production of Plybamboo in the previous calculation, can also be used directly as a material in various applications. Therefore, in this environmental impact assessment the bamboo stem was also compared with alternatives in wood. The environmental costs per kilogram during the production and transport of the bamboo stem were calculated for a 5.33 m long bamboo stem from the Moso species. For the calculations the reader is referred to appendix A. In table 2.10 the eco-costs per kilogram of a Moso stem are depicted. In figure 2.10 the contribution of each process step to the eco-costs per kilogram is presented.

Table 2.10: Eco-costs per kilogram of a 5.33 m Moso stem

Product	Eco-costs (€)/kg
Moso stem	0.842

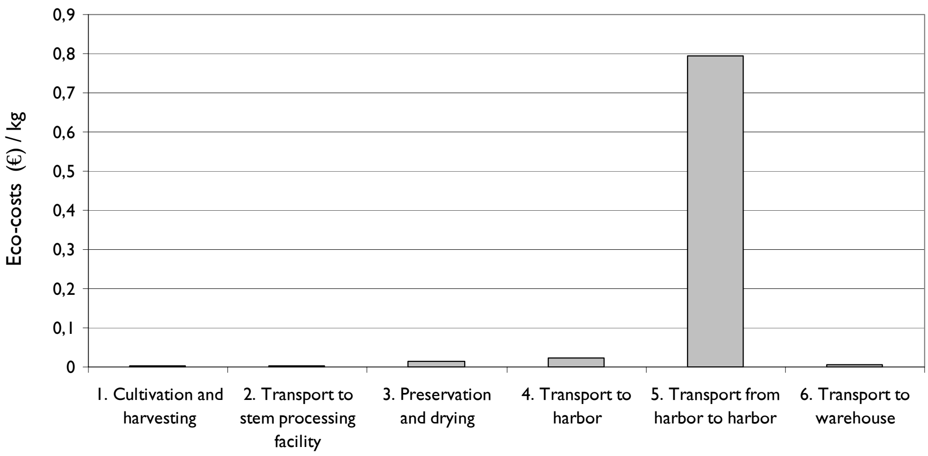

Figure 2.10: Environmental impact (eco-costs in €/kg) of the various process steps during the production and transport of a Moso stem

From figure 2.10 two important conclusions can be drawn: 1) the bamboo stem goes through very few processing steps; besides the transport steps, after harvest and preservation bamboo can directly be used as input for applications, which shows the efficiency of the material (e.g. a tree is almost never used in its natural form in applications); and 2) almost all the environmental costs of the bamboo stem (94.5%; see table A8 in appendix A) are caused by the sea transport of the stems from China to the Netherlands. Due to the large volume bamboo stems occupy in the container, the transport of the material to a very large extent determines the eco-burden of the material, since for low weight sea transports the eco-costs are calculated based on the eco-costs per m3.km of the boat used (see for more details appendix A).

Eco-costs per FU

As mentioned before, the eco-costs/kg do not say a lot unless a material is compared with other materials in a certain FU, in which both materials fulfill requirements for the same function. The unique properties of the stem are mainly its lightness and distinct aesthetic look. For the environmental assessment, a leg of the table developed during the project "Dutch Design meets Bamboo" by Ed van Engelen (not taking into account coating), was chosen as a FU.

Figure 2.11: Bamboo table designed by Ed van Engelen

In this particular application the size of the leg is determined by the aesthetics of the table. Only for very thin legs, buckling and compression strength may become the critical property. Therefore, in this FU bamboo was compared with various softwood and hardwood species from plantations (Poplar, Pine, European Beech, European Oak and Teak) based on similar dimensions as the bamboo version: round legs of 0.8 m long with a diameter of 9 cm, resulting in a volume of the leg of 0.0051 m3. The weight of the bamboo stem was calculated with the average weight per m1 of a 5.33 m long stem based on table 3.3 in section 3.2: 1.44 kg/m1, which equals 1.15 kilogram for a 0.8 m long segment. The results of the eco-costs per FU of bamboo compared to wood are represented in figure 2.12 and table 2.11, with in the final column of the table the ratio of eco-costs of the wood alternatives compared to bamboo. Note that in the calculation the life span, maintenance and end-of-life scenario is assumed not to be differentiating for the various alternatives in this application.

Table 2.11: Eco-costs per table leg for various wood- or bamboo based alternatives

Material	Density (kg/m3)	Eco-costs/kg	Kg/FU	Eco-costs (€)/FU	Eco-costs/FU (ratio)
Bamboo stem	700	0.842	1.15	0.97	100%
Bamboo stem (use in China)	700	0.046	1.15	0.05	5%
Scots Pine	500	0.05	2.55	0.13	13%
European Beech	670	0.04	3.42	0.14	14%
European Oak	700	0.04	3.57	0.14	14%
Poplar	440	0.03	2.24	0.07	7%
Teak (plantation)	650	0.21	3.32	0.7	72%
Teak (FSC)	650	1.70	3.32	5.64	581%

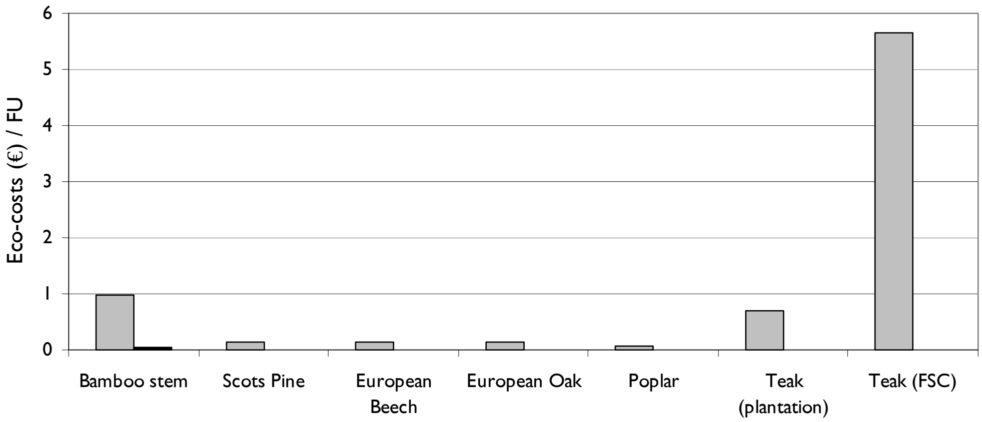

Figure 2.12: Eco-costs per table leg for various wood- or bamboo based alternatives

From figure 2.12 and table 2.11 several conclusions can be drawn. First of all can be seen that despite the low weight of the hollow bamboo stem (1.15 kg) compared to the solid legs made from wood (2.3 - 3.6 kg), due to the high eco-costs/kg caused by the sea transport, the bamboo stem has a higher environmental burden than almost all wood alternatives (except FSC tropical hardwood and tropical hardwood derived from natural forests). In case the bamboo stem is used locally (in this case in China), the eco-costs/FU will be drastically lower (see black column in figure 2.12), and the bamboo stem performs even better than locally grown wood species (see table 2.11).

In the box below, another comparison of the eco-costs was made between the bamboo stem and wood, this time for the use as a structural element in a walking bridge.

Box: The Eco-costs of the Bamboo Stem and Wood in a Walking Bridge

Figure 2.13: The bamboo walking bridge in the Amsterdam Woods

An earlier LCA calculation, based on the TWIN 2002 model (van der Lugt et al. 2003), has been recalculated based on the eco-costs 2007 method. The use of bamboo and wood in a transversal supporting beam (2.1 m) in a walking bridge in the Amsterdam Woods in the Netherlands was taken as FU (see figure 2.13 for photos of the actual bridge executed in steel and bamboo). Bamboo was compared with two hardwood species (one European species and one tropical species) known for their suitability for outdoor use: Robinia and Azobé. The exact dimensions of the beam were determined to meet strength requirements (0.1 × 0.2 × 2.1m for Azobé, and 0.12 × 0.225 × 2.1m for Robinia). In the original calculation, Guadua stems from Costa Rica were used for bamboo. Since the eco-costs calculation is executed for Moso, and Moso is a smaller and in general weaker species than Guadua, it is assumed that two Moso poles of 2.1 meters and a diameter of 9 cm are required with an average weight of 1.44 kg/m1, instead of one Guadua stem.
In this particular application, the durability outside differs for the various materials. So the life span needs to be taken into account for a comparison (Azobé 25 years, Robinia 15 years, Bamboo 10 years) (van der Lugt et al. 2003). As a reference, a steel beam (IPE 100, 22.3 kg, life span of 50 years) was also taken into account in this particular comparison. The results of the eco-costs per FU of bamboo compared to the alternatives are represented in figure 2.14 and table 2.12.

Table 2.12: Eco-costs per year for bamboo and wood used as a transversal beam in a walking bridge

Material	Density (kg/m3)	Eco-costs/kg	Kg/FU	Eco-costs (€)/FU	Eco-costs (€) per FU per year	Eco-cost per FU per year (ratio)
Bamboo stem	700	0.842	6.0	5.05	0.51	100%
Bamboo stem (use in China)	700	0.046	6.0	0.276	0.03	5%
Robinia	740	0.05	42.2	2.11	0.14	27%
Azobé (plantation)	1060	0.09	44.5	8.19	0.33	62%
Azobé (from FSC certified plantation)	1060	0.86	44.5	38.28	1.53	303%
Steel	7850	0.487	22.3	10.86	0.22	43%

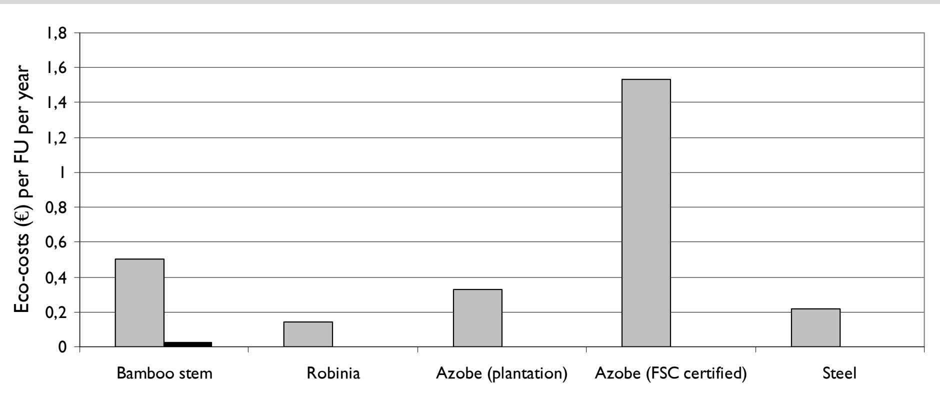

Figure 2.14: Eco-costs per year for bamboo and wood used as a transversal beam in a walking bridge

From the figure and table it can be concluded that, although the weight of the two bamboo stems combined in the function of transversal beam is the lowest of all alternatives, the eco-costs per FU per year are higher than all alternatives, except FSC certified Azobé.
In case bamboo is used locally (in China), the eco-costs of the bamboo stem are drastically lower (see black column in figure 2.14).
It is interesting to see that steel (with high eco-costs/kg) is the most environmental alternative in this particular application due to the relative low weight of the I-profile compared to the massive wooden beams, and the long life span of steel (50 years).

2.5 Fibers

Bamboo fibers may be used as reinforcement in natural fiber reinforced composites suitable in various applications. Since production data of fibers was not available, they were not assessed for the eco-costs calculation. However, to provide some indication of the energy consumption during production of glass fibers (most often used in composites), carbon fibers and cellulose fibers (such as bamboo fibers), the reader is referred to table 2.13.

Figure 2.15: Bamboo micro fibers

Table 2.13: Energy consumption during production of several fibers (Kavelin 2005)

Fiber	Energy consumption during production (MJ/kg)
Cellulose	4
Glass	30
Carbon	130

Note that in this table the density of the materials and the FU is not yet taken into account; however, independent of these features, natural fibers seem to score quite well. Nevertheless, compared to other popular natural fibers (e.g. sisal, flax, hemp, jute, various wood species), bamboo needs to go through more processing steps before the fiber is distilled and/or has to be transported from further away. Therefore, it may be questionable if bamboo will be very competitive compared to other natural fibers in terms of eco-costs for use in Western Europe. This might be different for production of natural fiber based composites for local use, especially if researchers are able to efficiently distill the bamboo fiber from the stem without too many material losses, in order to utilize the large annual increase in biomass (see chapter 3).

2.6 Strand Woven Bamboo

Figure 2.16: Samples of Strand Woven Bamboo (SWB)

Strand Woven Bamboo (SWB) is a relatively new industrial bamboo material that can be used indoors and outdoors, with a high hardness (2800 lbf) and density (1080 kg/m3) due to the compressed bamboo strips used in combination with a high resin content. The eco-costs calculation was based on the outdoor version (with a higher glue content and higher compression level) in a carbonized color. The eco-costs per kilogram calculation was based on the production and transport of one SWB plank of 1900 x 100 x 15 mm (0.00285 m3). For the complete calculation the reader is referred to appendix A. The eco-costs per kilogram for SWB are presented in table 2.14. In figure 2.17 the contribution of each process step to the eco-costs per kilogram is presented.

Table 2.14: Eco-costs per kilogram of SWB

Product	Eco-costs (€)/kg
SWB (carbonized)	0.524

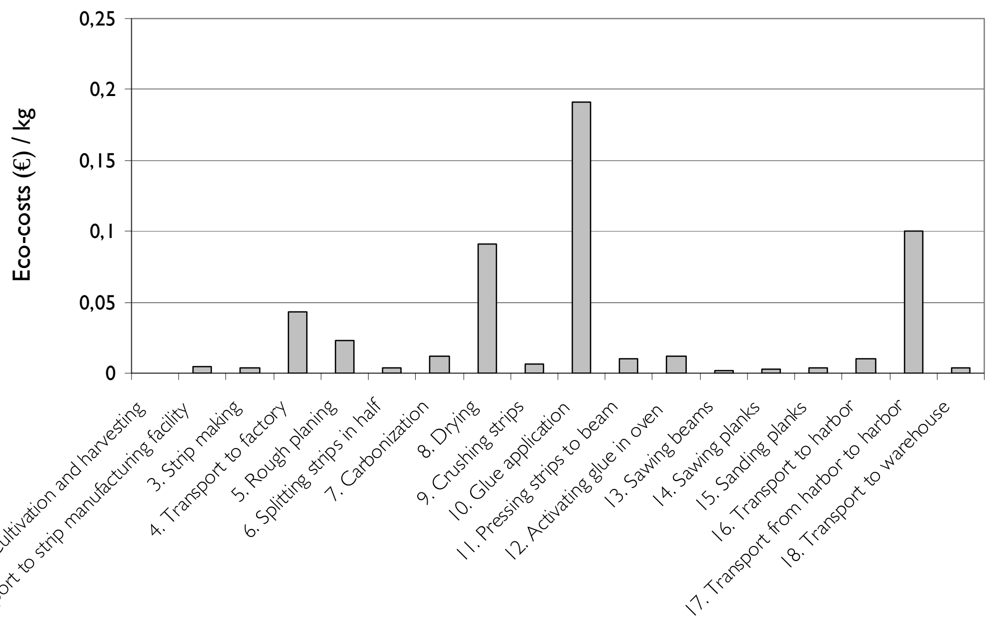

Figure 2.17: Environmental impact (eco-costs in €/kg) of the various process steps during the production and transport of a SWB plank

From figure 2.17 it can be concluded that the Phenol Formaldehyde resin used (23% in the final product) has a large impact on the eco-costs/kg of SWB, accounting for 36.4% of the environmental burden. For more background information, the reader is referred to appendix A.

Eco-costs per FU

One of the unique features of SWB is that, unlike other industrial bamboo materials, it seems suitable for use outdoors (van der Vegte and Zaal 2008); for more information see footnote 9 in section 1.4. For this reason, the eco-costs of SWB were compared with wood alternatives in the function of terrace decking (FU) for outside use with dimensions of 1900 x 100 x

15 mm (0.00285 m3). In this application, besides aesthetics, the durability outside is the most important criterion for material selection, based on which alternatives for comparison with SWB were selected. Various tropical hardwood species (e.g. Teak, Azobé, Bangkirai) are well known for their durability outside. For the eco-costs calculation SWB was compared with Teak and Azobé, although Teak is the commonly used alternative for this application. Although Azobé is more often used in more demanding applications such as in bridges, this species was chosen for this calculation as a representative of a tropical hardwood species with relatively low eco-costs/kg (see table 2.1). Since tropical hardwood is often used in outdoor applications, and it often is unclear if this wood is sourced from natural forests or plantations, the eco-costs for various scenarios (plantation, FSC certified, RIL harvested from natural forest) were calculated for Teak and Azobé.

Another method to increase the outdoor durability of timber is to modify softwood through impregnation, thermal modification or acetylation.
Impregnation is only functional if heavy metals (e.g. chrome, copper, arsenic) are used, which are poisonous for humans and will be released in the environment once the wood is disposed of. Impregnated wood has therefore received a lot of resistance in the West ("poison wood") and is increasingly being replaced by supposedly more eco-friendly techniques to modify softwood. For this reason impregnated wood was not taken into account in this calculation.
Thermal modification is a more environmental friendly option. The durability of softwood is improved considerably through thermal treatment. There are several producers of thermally modified wood each using slightly different parameters. For this report, production data on Plato® Wood from European Spruce was used to calculate the eco-costs: 0,13 €/kg.
Acetylation is another method that is currently being commercialized, that can be used to modify the durability of softwood. In this chemical process wood reacts in kettles with acetic anhydride, through which free hydroxyls in the wood are formed into acetyl groups. According to Titan Wood (2008), the producer of acetylated wood, the process is 100% recyclable and non-toxic. An advantage of this method is that, as opposed to thermal modification, the mechanical properties of the treated wood slightly improve, which facilitates a larger range of applications for Accoya® (the trade name of acetylated wood) in constructive applications (e.g. bridges) compared to thermally modified wood. An LCI of the production data of acetylated wood can be found in Classen and Caduff (2007). Calculation shows that the acetylation process of Scots Pine results in eco-costs of 0.22 €/kg of Accoya.

Finally, a wood-plastic composite was also taken into account for this calculation; Tech-Wood® is a material which consists of 70% of Pine fibers and 30% of polypropylene (Tech-Wood 2008). As such the eco-costs/kg of the Pine fiber input for Tech-Wood accounts for 0.05 x 0.7 = 0.035 €/kg. The eco-costs/kg of the Polypropylene part are 0.3 x 1.02 (eco-costs/kg of polypropylene) = 0.306 €/kg. In total the eco-costs/kg for Tech-Wood are then 0.341 €/kg.

In table 2.15 and figure 2.19, the eco-costs per FU of the various alternatives are depicted. In the final column of the table the ratio of the alternatives compared to SWB is provided. The eco-costs/FU are calculated based on the same dimensions of the decking plank as for SWB (1900 x 100 x 15 mm = 0.00285 m3), except in the case of Tech-Wood. Since Tech-Wood profiles are made through a "push-trusion" process, around 40% less material is required (see figure 2.18) than for a solid alternative. The density of Tech-Wood was based on the density and volume percentage of Pine (500 kg/m3) and Polypropylene (900 kg/m3). Because of thermal modification the weight of Plato® wood decreases by approximately 10% (Boonstra 2008), whereas the weight of Accoya® increases by approximately the same number (de Groot 2006), which was taken into account in table 2.15 below.

Figure 2.18: Sample of a Tech-Wood decking profile

Table 2.15: Eco-costs per year for SWB and alternatives for outside terrace decking

Material	Density (kg/m3)	Eco-costs/kg	Kg/FU	Eco-costs (€)/FU	Eco-costs/FU (ratio)
SWB	1080	0.52	3.08	1.61	100%
Teak (plantation)	650	0.21	1.85	0.39	24%
Teak (FSC certified)	650	1.70	1.85	3.15	195%
Teak (natural forest; RIL)	650	7.67	1.85	14.19	881%
Azobé (plantation)	1060	0.09	3.02	0.27	17%
Azobé (FSC certified)	1060	0.86	3.02	2.60	161%
Azobé (natural forest; RIL)	1060	3.96	3.02	11.96	742%
Plato wood	420	0.13	1.20	0,16	10%
Acetylated wood	550	0.22	1.56	0.34	21%
Tech-Wood	620	0.34	1.77	0.60	37%

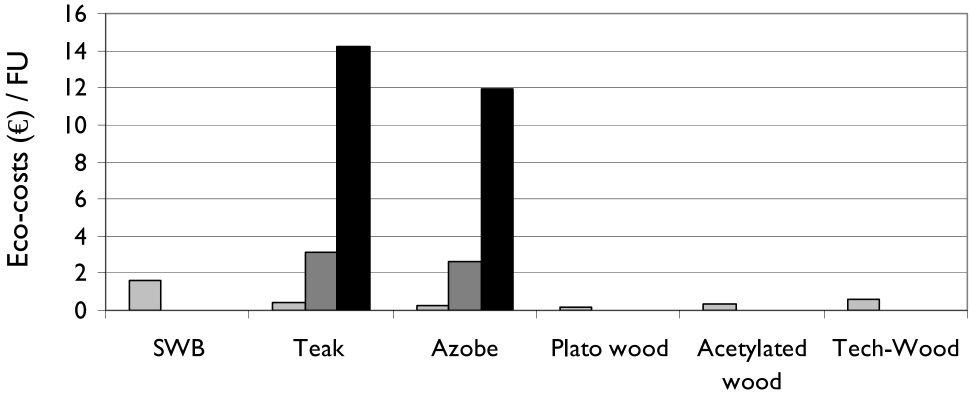

Figure 2.19: Eco-costs per year for SWB and alternatives for use in outside terrace decking
Note: for Teak and Azobé the light gray bar refers to plantation grown timber, the dark gray bar for FSC certified timber (unclear if from forest or plantation, see section 2.2) and the black bar refers to timber derived from natural forests.

From figure 5.19 it can be concluded that SWB has an environmental burden that is higher than for modified softwood (Plato wood and Accoya), Tech-Wood and suitable plantation grown tropical hardwood species (in this case Teak and Azobé). However, it has a lower environmental impact than FSC certified Teak and Azobé, and Teak and Azobé harvested from natural forests.

If SWB is used locally, the eco-costs will be considerably lower, since sea transport accounts for 19.2% of the total environmental burden, see table A9 in appendix A. For inside applications it would be worthwhile to investigate to what extent the Phenol formaldehyde resin in SWB could be replaced by completely biodegradable resins such as PLA. It can be concluded that in terms of eco-costs the use of SWB is recommended to help meet the growing demand for tropical hardwood sourced from natural forests (including FSC certified timber), although better performing alternatives from an environmental impact point of view (Tech-Wood and modified timber) are available and should receive priority.

2.7 Bamboo Mat Board

Figure 2.20: Bamboo mats are available "on the roll"

In Asia thin bamboo slivers and strips are commonly woven into large mats, which can serve as input for the production of various boards, including Bamboo Mat Board (BMB) which can be pressed into molds of various shapes (including corrugated boards). Since the production[15] and density (1030 kg/m3) of BMB (BMTPC 2002) and SWB are very similar and both materials use a large amount of resin, it was assumed for the calculation that the eco-costs/kg of both materials are similar.

Figure 2.21: Chair made from bamboo mats, designed by Maarten Baptist

To compare BMB with alternatives on eco-costs, the molded seating as designed by Maarten Baptist during the project "Dutch Design meets Bamboo" (van der Lugt 2007) was chosen as FU. Since one of the unique properties of BMB is that it can be molded in three directions at the same time to form 3D structures, it was assumed that the seating was executed as a bowl (instead of the 2D bended seating in figure 2.21). It is assumed that for the seating a piece of 0.4 x 0.4 x 0.015 m (0.0024 m3) BMB is required. Since 3D bending is not possible in wood, as a reference the calculation was also executed in ABS, a high end polymer suitable for use in 3D bowls. For the calculation it was assumed that the ABS alternative can be produced in a slimmer version than the bamboo alternative: 0.4 x 0.4 x 0.003 m (0.00048 m3). In table 2.16 and figure 2.22 the eco-costs/FU for BMB and the various alternatives are represented.

Table 2.16: Eco-costs per year for BMB and alternatives used in a 3D molded seating

Material	Density (kg/m3)	Eco-costs/kg	Kg/FU	Eco-costs (€)/FU	Eco-costs/FU (ratio)
BMB	1030	0.524	2.47	1.30	100%
ABS	1100	1.32	0.53	0.70	54%

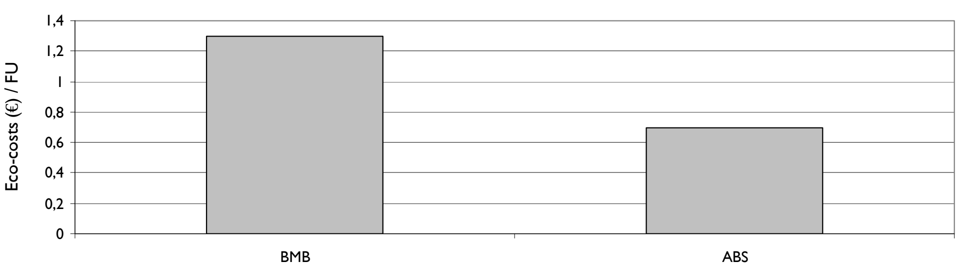

Figure 2.22: Eco-costs per year for BMB and alternatives for use in a 3D molded seating

[15] According to Zhang Qisheng et al. (2003) the BMB production process is as follows: Strip making > weaving > glue application (usually phenol formaldehyde) > drying > hot pressing (in mold) > sawing.

From figure 2.22 it becomes clear that in this particular application BMB has an even higher environmental burden than ABS, which is one of the least environmentally friendly polymers. For local use the eco-costs might also be lower since sea transport will not play a role in that scenario. Furthermore, the environmental burden of BMB could be diminished by deploying a biodegradable resin such as PLA instead of Phenol formaldehyde.
Note that in the case of 2D bending, Beech, Plywood and Plybamboo are also eligible, which, due to the lower density and eco-costs per kilogram will have lower eco-costs when used in molded seatings (see section 2.3).

In the box below, an example is provided about an eco-costs comparison of corrugated BMB roof sheets based on use in China.

Box: Eco-costs of BMB Corrugated Roof Sheets Based on Use in China

BMB is often also used in China and India as corrugated roof sheet. The production process is similar to the production process of regular BMB with the exception that the material is hot pressed in a mold (Zhang Qisheng et al. 2003). Furthermore, for the eco-costs per kilogram the eco-costs of transport (sea- and land transport to the Netherlands, see appendix A) should be deducted to acquire eco-costs for the local situation resulting in eco-costs/kg of € 0.419.

Figure 2.23: Corrugated board made from BMB

Corrugated BMB targets the low cost housing market in India and China and should therefore be compared with other low cost alternatives often used in these countries: corrugated steel sheet or corrugated PVC sheet. The alternatives were compared based on 1 m2 of roof sheet (FU). Corrugated sheets in steel (thickness 0.6 mm) and PVC (thickness 2 mm) are thinner than BMB (thickness at 3.7 mm, see BMTPC 2002), thus a smaller amount of material is required for these alternatives. In table 2.17 and figure 2.24 the eco-costs per FU are represented. Note that in the calculation it is assumed that all alternatives have the same life span.

Table 2.17: Eco-costs per year for BMB and alternatives for use for in a corrugated roof sheet

Material	Density (kg/m3)	Eco-costs/kg	Kg/FU	Eco-costs (€)/FU	Eco-costs/FU (ratio)
BMB	1030	0.419	3.81	1.60	100%
PVC	1450	0.64	2.90	1.86	116%
Steel sheet	7850	0.487	4.71	2.29	144%

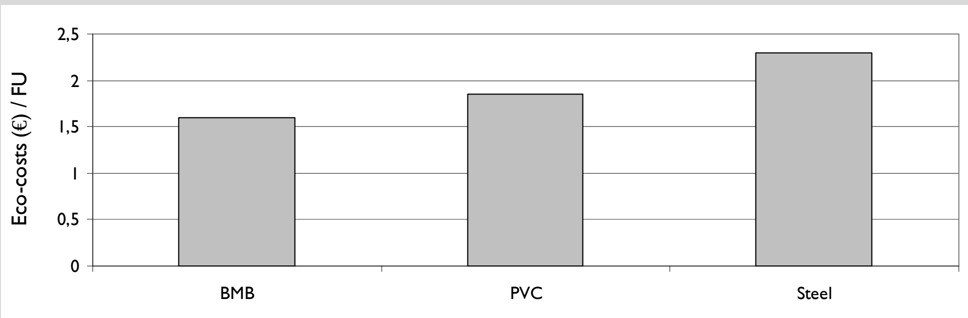

Figure 2.24: Eco-costs per year for BMB and alternatives for use for in a corrugated roof sheet

The figure and table show that if used locally, and if no plantation based wood alternatives are around for a particular application, industrial bamboo materials such as BMB can compete on eco-costs with non-wood alternatives in applications such as corrugated roof sheets.

3 Land-use and Annual Yield

3.1 Introduction

In the previous chapter the environmental impact (in eco-costs) of various bamboo materials was calculated determining the debit side of the environmental sustainability of these materials. As seen in section 1.2, due to the increasing population and consumption per capita the Ecological Footprint is growing, resulting in more hectares required to produce the required resources compared to the biocapacity planet Earth offers. Due to the high growing speed of bamboo, the annual yield per hectare of bamboo could be higher than for wood, which would mean from a global point of view it would be more efficient in the future to plant bamboo on a hectare of vacant land as compared to trees to help to meet the increasing global resource demand. Therefore, in this chapter the annual yield of bamboo compared to wood will be investigated as the environmental sustainability component at the credit side of the total environmental sustainability balance (see table 1.5).

As was also the case for the eco-costs calculation, many assumptions need to be made for the annual yield calculation and evaluation for bamboo, compared to wood. The annual yield comparison is based on sustainably managed bamboo- and wood plantations. For the calculation it was assumed that the annual yields of these plantations are used in industries with a high consumption of renewable materials: the building industry and the interior decoration industry (used in this report to define the market for furniture & interior design applications). The annual yield and production efficiency calculation is based on current practices in the most advanced regions for processing for wood and bamboo: the wood industry in Europe and North America, and the bamboo industry in China.
For wood, the raw material that is sourced from a plantation annually (logs), is processed into sawn timber, veneer or various wood based boards (e.g. Plywood, MDF, chipboard, composites, etc.), which are the semi finished materials used as input in the industries mentioned. For giant bamboo species the annual yield of a plantation will be used for the production of semi finished materials such as Plybamboo, SWB, BMB, stems, taped mats (mostly for the interior decoration industry) as well as similar board materials as available in wood (MDF, chipboard, composites, etc.). Taped mats are made from thin bamboo strips that are woven or taped together to form mats that can be used, for example, as flooring or wall coverings (see figure 3.1). The eco-costs of taped mats may be expected to be somewhat lower than 1-layer Plybamboo board (no glue application, less processing steps).
Although some additional material losses will take place during the transformation of the various semi finished materials into the final consumer product, it was assumed that material losses during the process semi finished material > final consumer durable for both bamboo and wood are similar, and therefore not differentiating.

Figure 3.1: Taped mats are available in various colors

For wood, the annual yield was calculated for the following species that are commonly used in the industries mentioned: Teak, European Oak and Eucalyptus. For Teak, the annual yield was calculated for both fast growing "baby Teak" and traditional Teak. Eucalyptus is commonly used in the paper industry (Wiselius 2001) and only in rare occasions in the interior decoration industry, but is used as an interesting reference in this annual yield calculation due to its reputation as one of the fastest growing tree species. The value of the density used for the various wood species in this chapter was derived from Wiselius (2001).

For bamboo, the annual yields were calculated for the giant bamboo species Moso from China, and Guadua from Latin America, based on a density for both species of 700 kg/m3.[16] Guadua is a giant clumping bamboo species which grows

[16] Note that depending on the local circumstances even for exactly the same bamboo species the density can differ.

abundantly in Latin America. Guadua may reach heights up to 20-25 meters and diameters up to 22 cm (Riaño et al. 2002). Like most bamboos it reaches its final height in the first half year of its growth (with a growing speed up to 21 cm a day), and will come to maturity in the following 4-5 years (Riaño et al. 2002). It should be noted that currently, production of industrial bamboo materials such as Plybamboo in Latin America is negligible compared to China. Thus, the annual yield of Guadua in terms of semi finished materials is only included as a reference for the future potential of Guadua for this purpose. The calculation for both wood and bamboo will be based on numbers for average plantation sites. 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. Data is based on interviews with experts in wood growing and processing (Mr. Leen Kuiper of Probos Foundation, and Mr. Hessel van Straten of NIBO N.V.) and bamboo growing and processing (Mr. René Zaal of Moso International), and supplemented where necessary with findings from key literature.

3.2 Results

Before the results of the annual yield calculations for wood and bamboo are presented in this section, the production efficiency of both renewable resources needs to be introduced.

Production Efficiency

In essence, the production process of wood- and bamboo resources to semi finished materials (sawn timber for wood, boards for Plybamboo, and beams for SWB) is similar. For wood the resource (the tree) will be cut in the field, after which the bark, sapwood and branches will be removed to acquire so-called "logs". After processing (e.g. sawing, drying) semi finished materials (sawn timber, board materials) are acquired. For bamboo the harvested stems, once the branches are removed, are in a similar processing stage as the logs for wood. Just like for wood, these stems may be further processed into all kinds of semi finished materials as well. If a large portion of the original harvested natural material on the plantation (harvestable standing volume) ends up in the semi finished material this means the production efficiency is high, and material losses in the production process are low.

A processor or material producer will in general manufacture the semi finished materials with the highest turnover per hectare, which for wood, depending on the species, may result in the production of wood based boards such as Plywood or MDF (usually less added value but higher quantities per hectare) or sawn timber (usually higher added value but lower quantities). Suitability for the production into a certain semi finished material will differ per wood species. In the building and interior decoration industry, in general, hardwood will be used in applications with higher quality requirements than softwood, and will therefore to a larger extent be processed into sawn timber (higher added value) than softwood (to a larger extent used in wood based boards). For bamboo, Plybamboo boards may offer most added value, followed by SWB, taped mats, BMB, the stem and various board materials also available in wood (e.g. MDF). Table 3.1 summarizes which semi finished materials wood and giant bamboo species may be processed into, with the materials with most added value represented first (A-quality).

Table 3.1: Semi finished materials into which wood and bamboo may be processed as input for the building or interior decoration industry, ranked in categories with most added value

Quality	Wood	Bamboo
A (highest added value)	Sawn timber	Plybamboo
	Veneer	Veneer
		SWB
		Taped mats
B (low - medium added value)	Various board materials (Plywood, MDF, chipboard, etc.)	Same board materials as in wood (MDF, chipboard, etc.)
	Composites	Composites
		BMB
		Stem
C (lowest added value)	Biofuel (may be used as energy source for production of semi finished materials above)	Biofuel (may be used as energy source for production of semi finished materials above)

Since the annual yield of bamboo and wood may differ depending on the kind of semi finished materials produced, the annual yield was calculated for various production scenarios:
A: The annual yield is completely allocated to the production of A-quality semi finished materials
B: The annual yield is completely allocated to the production of B-quality semi finished materials

Depending on the local socio economic situation (e.g. prevalent species, trends in demand, etc.) either scenario A or B will be most realistic. Below, the production efficiency for both wood and bamboo are estimated based on these production scenarios A and B, starting with wood.

Wood

For production scenario A (production of sawn timber), for wood, as a general rule of thumb, it is assumed that 80% of the total standing volume of a plantation ready for harvesting may end up in logs. When sawing the logs into timber it is assumed that over half of this volume is lost in saw mill residues, and a little less than half will end up in sawn timber (30-40% of standing volume in the plantation); see figure 3.3 (Kuiper 2006, van Straten 2006). It should be noted that this rule of thumb is very rough and may be lower or higher depending on the dimensions of the semi finished material (and eventual final application) in which the resource will be used, as well as the diameter and straightness of the trunk, which is species and site dependent. Although rest material (saw dust, etc.) may be used as input for B-quality materials (e.g. MDF), in most saw mills the rest material that is produced during processing logs into sawn timber is used as biofuel (C-quality application; see figure 3.3) to power the various machines (saws, kilns, etc.) (Bergman and Bowe 2008).

For production scenario B the annual yield calculation for both wood and bamboo is based on the production of MDF as a typical B-quality material. MDF is produced by chipping logs into fine fibers which in combination with resin are pressed into stiff boards. Since the input material is chipped to small fibers, there are hardly any input requirements for the raw material. For the production from the logs (80% of standing volume; see before) to the final boards an additional material loss during processing of 20% is assumed, resulting in a production efficiency of 64% (see figure 3.3).

Bamboo

Production scenario A for bamboo is different than for wood due to raw material allocation. In general, for wood, due to the large sizes and heavy weight of logs, the annual yield will be completely processed into one kind of semi finished material (e.g. sawn timber or wood based boards). In general, for bamboo, due to the smaller size and lower weight per stem the annual yield per hectare in stems can be more easily divided after quality control and sold in separate bunches to various processors and manufacturers depending on the quality of the stems (best stems go to the Plybamboo industry; the other stems go to the taped mats and/or SWB industry) (Zaal 2008). Therefore, the yield from a bamboo plantation is used as input for various A-quality materials; see figure 3.3. During processing of the harvested mature stems (around age 4 for Moso, around age 5-6 for Guadua) from the plantation (harvestable standing volume) to the debranched and topped stems a 20% loss is assumed.[17]

Of the harvested stems only a portion meets quality requirements for use as input for the production of Plybamboo boards (see complete production process of Plybamboo in appendix A). Due to the high requirements posed to the input strips in Plybamboo during the production process of selected stems into Plybamboo an additional 60% of the material is lost (Zaal 2008), which is commonly used as biofuel in the same factory, corresponding with a production efficiency of around 32%.

For the production of taped mats, the efficiency is higher since the input strips may be smaller (meaning that more strips may be derived from the upper segments of the stem with lower wall thickness), and quality requirements are lower. According to Zaal (2008) during the production of mats from the debranched and topped stems an additional 40% of the material is lost (used as biofuel), resulting in an efficiency of taped mats production of 48%.

For SWB, quality requirements of input strips are even lower since the strips are compressed in the final product, resulting in a lower material loss of 30% (Zaal 2008) than for the taped mats and Plybamboo boards, which corresponds to a production efficiency of 56%.

If is assumed that 50% of all annually harvested stems are apt to produce Plybamboo, and the other half is divided for use in the taped mat industry (25%) and SWB industry (25%); the total production efficiency during the conversion of the harvestable standing volume in a bamboo plantation to A-quality bamboo materials can then be determined at 42% (Plybamboo: 50% x 32% = 16%; taped mats: 25% x 48% = 12%; SWB: 25% x 56% =14%); see figure 3.3. This shows that efficiency for the production of A-quality materials is higher for bamboo (42%) than for wood (35%). As a result, during the production process of sawn timber more rest material is produced, which is used as biofuel during the production process, which results in lower eco-costs in energy use for the production of sawn timber compared to the production of industrial bamboo materials such as Plybamboo, since this internal system use of biofuel prevents the consumption of additional electricity.

For production scenario B the efficiency for the production of bamboo based MDF is similar to the production of wood based MDF board production (64%).

[17] Note that in the Chinese bamboo industry even this top may be used, for example, for the production of handicraft or broomsticks.

Figure 3.2: Low quality bamboo material used as input (left) for the production (center) of bamboo based MDF (right)

In figure 3.3 below the production efficiency of both a bamboo plantation and a wood plantation is depicted visually for scenario A and B. Note that although not depicted in the figure, the high quality bamboo stems used as input in the Plybamboo industry can also be used directly as a B-quality material, obviously with low material losses, which depends on the quality requirements of the application in which the stem is used (e.g. scaffolding versus high end country house). For the production of A-quality materials for both bamboo and wood, it applies that rest material and waste can hypothetically be used as input in B-quality materials (e.g. MDF) but in practice is usually used as biofuel in the factory itself (C-quality).

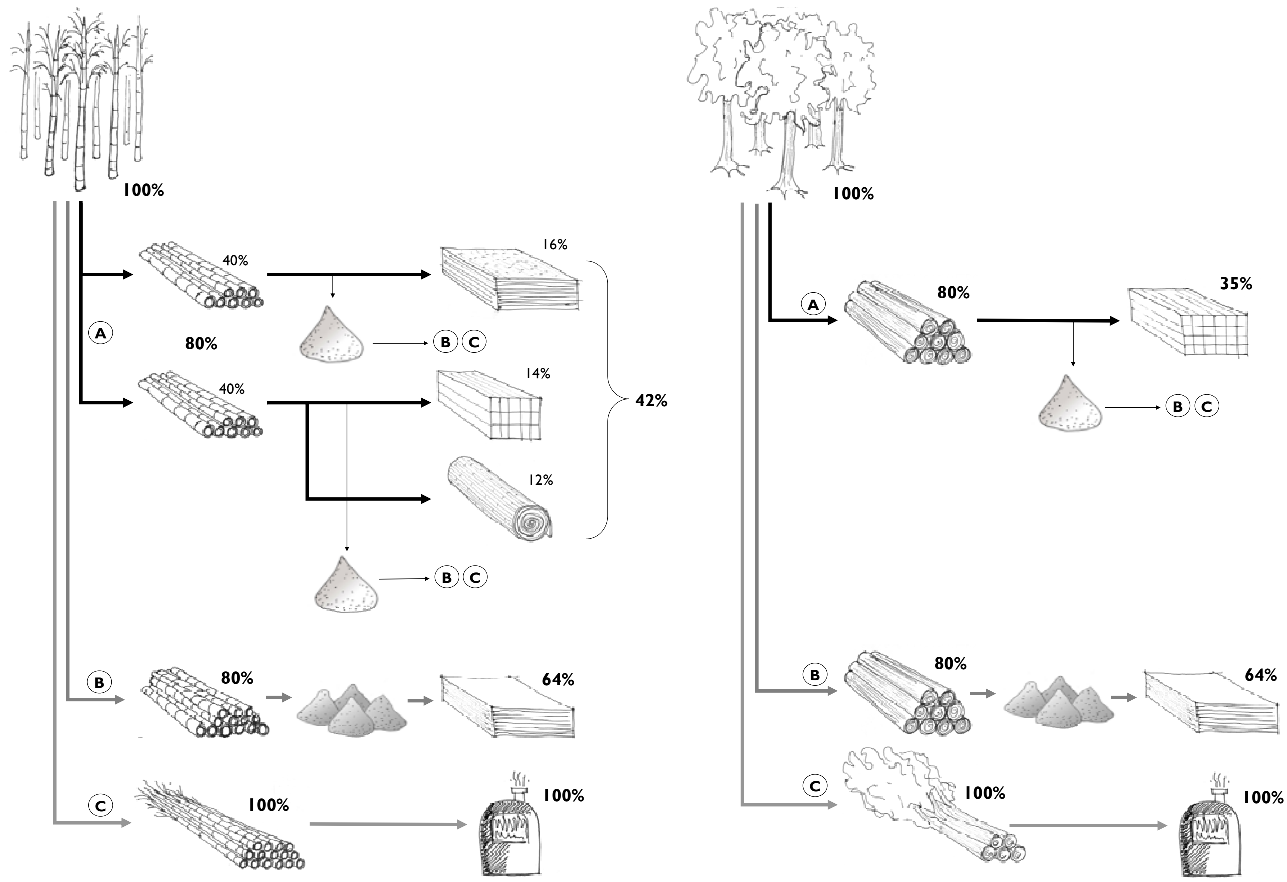

Figure 3.3: Efficiency during the conversion of bamboo (left) and wood (right) resources to semi finished materials; all percentages related to harvestable standing volume (100%)

Annual Yield

<u>Wood</u>

First, the average figures of the annual yield in terms of cubic meters of semi finished materials are presented for a hectare of sustainably managed wood plantation for both production scenario A and B. Although wood is usually harvested in multi year cycles (e.g. 15 years), the annual yield figure can be used as a base of comparison with bamboo. Again, it should be stressed that the figures mentioned may be considerably higher or lower depending on the climatic and geographic conditions of the plantation. It should be noted that in practice, due to the lower annual yields and low input requirements, fast growing softwoods will be used for the production of MDF and hardwood will not. Therefore, in table 3.2 only the annual yields of MDF in softwood are depicted. Note that for MDF, the wood fibers are combined with resin and compressed 1.5 times.

Table 3.2: Estimates of the annual yield of semi finished materials sourced from a wood plantation (Kuiper 2006, van Straten 2006, Wiselius 2001)

Wood species	Annual increase in standing volume (m3/ha)	Annual yield in logs (m3/ha)	Scenario A: Annual yield in sawn timber (m3/ha)	Scenario B: Annual yield in MDF (m3/ha)
Baby Teak	12.5	10	4.4	N/A
Regular Teak	6	4.8	2.1	N/A
European Oak	5	4	1.8	N/A
Eucalyptus	25	20	8.8	10.7

<u>Bamboo</u>
The annual yield calculation for A-quality bamboo materials is based on the number of bamboo stems that can be annually harvested in a sustainable manner from a Moso and Guadua plantation. While the harvest of a wood plantation is often based on multi year rotation cycles, since one bamboo plant consists of various stems and reproduces new stalks each year, for maximum yields a bamboo plantation is harvested every 1-2 years. During this harvest only the mature culms (4 years for Moso, 5-6 years for Guadua) should be felled for sustained maximum annual yields for material production.

According to Riaño et al. (2002) a typical Guadua plantation houses 3000-8000 stems. For this calculation an average of 5000 stems per hectare was assumed, which can be considered a conservative estimation. Since Guadua stems mature in 5-6 years, the yield was calculated with an annual harvest of 1/6 of the stems which results in an annual yield of 833 stems/ha. According to Zaal (2008) a typical Moso plantation in China used for board and flooring production will contain approximately 3000 stems, with an annual harvest of 1/4 of the stems; this will result in an annual yield of 750 stems. For the calculation it was assumed that for the production of A-quality materials half of these stems (417 stems/ha for Guadua and 375 stems/ha for Moso) are used for industrial processing into Plybamboo boards, while the other half will be evenly divided as input in the taped mats- and SWB industry (2 x 209 stems/ha for Guadua and 2 x 188 stems/ha for Moso).
In the beginning of appendix A it is explained that industrially produced bamboo materials from China are based on the 2.66 m measure; based on an 8-meter long Moso stem, three segments can be cut that can be used as input for the strip- and board producing industry. Due to the tapering character of bamboo, the diameter and wall thickness of these three segments decreases from bottom to top, which means that from the bottom part more material can be sourced than from the middle- and top part. Guadua is a bigger bamboo species than Moso. Therefore, for Guadua it is assumed that four segments can be derived from a stem: 4 x 2.66 m = 10.66 m, assuming a similar production process as in China. Note that for the production of strips the uppermost part of the stem (above 8 m for Moso, above 10.66 m for Guadua) is not suitable and is assumed to be used as input for low value applications (e.g. biofuel, broomsticks, banana props).

As a rule of thumb, the wall thickness of most bamboos can be found with the formula $d = 0.82 * D$, with d = the internal diameter of the cavity of the bamboo and D = the external diameter. Since the diameter of Moso and Guadua stems was measured by the first author on various field studies in China and Latin America, the corresponding wall thickness was calculated with this formula for the various stem segments, based on which the material volume was calculated per stem with (π (=3.14) * (D^2 - d^2)/4) in order to determine the cross section of a bamboo stem, multiplied by the length (2.66 meters).

Table 3.3: The diameter, wall thickness, volume and weight of the various segments of a harvested Moso stem

Segment in the stem	Diameter (cm)	Wall thickness (mm)	Volume (m3) of solid material per segment (2.66 m)	Dry weight (kg) per segment (2.66 m)*
0 - 2.66	10	9	0.0068	4.79
2.66 - 5.33	8	7	0.0040	2.86
5.33 - 8	6	5	0.0027	1.87
Total stem			**0.0136**	**9.52**

* based on a density of 700 kg/m3

Table 3.4: The diameter, wall thickness, volume and weight of the various segments of a harvested Guadua stem

Segment in the stem	Diameter (cm)	Wall thickness (mm)	Volume (m3) of solid material per segment (2.66 m)	Dry weight (kg) per segment (2.66 m)*
0 - 2.66	12	11	0.0098	6.91
2.66 - 5.33	10	9	0.0068	4.79
5.33 - 8	8	7	0.0040	2.86
8 - 10.66	6	5	0.0027	1.87
Total stem			**0.0235**	**16.43**

* based on a density of 700 kg/m3

Based on the amount of stems, the production efficiency (see above) and the material volume per stem the annual yield of bamboo in cubic meters semi finished materials can be established (see table 3.5).
Note that for SWB, the bamboo strips are combined with resin and compressed 1.54 times into a composite material with a density of 1080 kg/m3 (see full production process in appendix A). For bamboo based MDF it is assumed that mature stems are required, while the compression rate is assumed to be 1.5 times. Besides scenario A and B, also a scenario is calculated in which all material deriving from a plantation is used for the production of SWB. Due to the increasing demand for tropical hardwood and the relative high added value of SWB this may be a realistic production scenario in the future.

Table 3.5: Estimates of the annual yield of semi finished materials sourced from a bamboo plantation

Bamboo species	Annual yield of suitable stems for semi finished material production (stems/ha)	Volume per stem[18] (m3/stem)	Efficiency in processing stems to semi finished material (%)	Annual yield semi finished material (m3/ha)
Moso: A-quality materials	Plybamboo: 375 Taped mats: 188 SWB: 188	0.014	Plybamboo: 40% Taped mats: 60% SWB: 70%	Plybamboo: 2.0 Taped mats: 1.5 SWB:1.2 **Total: 4.7**
Guadua: A-quality materials	Plybamboo: 417 Taped mats: 209 SWB: 209	0.024	Plybamboo: 40% Taped mats: 60% SWB: 70%	Plybamboo: 3.9 Taped mats: 2.9 SWB: 2.3 **Total: 9.1**
Moso: SWB	750	0.014	70%	4.6
Guadua: SWB	833	0.024	70%	8.8
Moso: B-quality materials (MDF)	750	0.014	80%	5.4
Guadua: B-quality materials (MDF)	833	0.024	80%	10.3

Bamboo vs. Wood
In figure 3.4 the results of the annual yield in cubic meters A-quality semi finished materials per hectare found in the tables above is summarized for various bamboo and wood species.

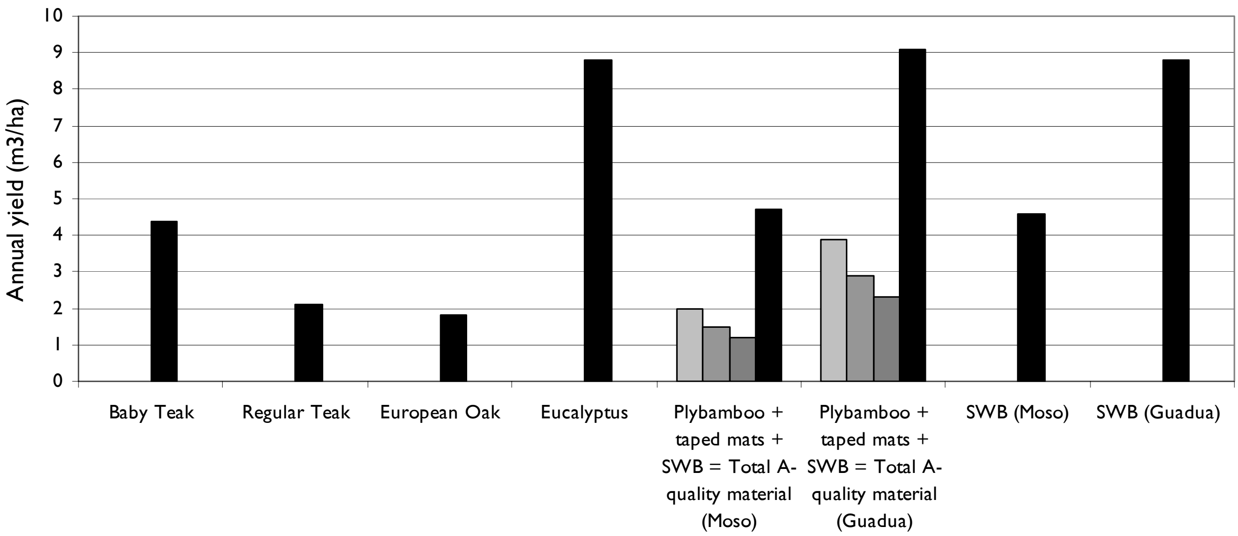

Figure 3.4: Estimates of the annual yield per hectare in cubic meters of bamboo- and wood based A-quality semi finished materials sourced from plantations
Note: For a just comparison of the total annual yield/ha for the various alternatives, the black bars should be compared

From figure 3.4 various conclusions can be drawn. For use in indoor applications all wood and bamboo species and materials depicted in the figure are applicable. Although in terms of A-quality materials Moso bamboo has a lower annual yield than Eucalyptus, due to its relatively low hardness, Eucalyptus will most often not be used in similar high end applications as Plybamboo, taped mats and SWB (e.g. flooring, tabletops), and may not serve as a good reference for these

[18] Applies to the debranched and topped stem, directly ready for input in the bamboo processing industry.

kinds of applications. Note that in the hypothetical (future?) situation that when these materials are made from Guadua the annual yields are almost twice as high as for Moso, and even higher than Eucalyptus.
Compared to one of the fastest growing hardwood species that is used in high end interior decoration (e.g. flooring), baby Teak, Moso has a slightly higher annual yield in terms of A-quality materials, while the hypothetical yield of Guadua is more than twice as high. Compared to other, slower growing hardwood species such as European Oak and regular Teak, the annual yields of A-quality materials made from Moso and Guadua are even higher, up to a factor five (Guadua compared to European Oak).

In the case of outdoor use, only some alternatives from figure 3.4 can be used due to their high durability outdoors (see figure 3.5 below). For bamboo only SWB is suitable for use outdoors, whereas in wood several tropical hardwoods such as Teak, but also modified Eucalyptus or Pine (e.g. thermally modified or acetylated wood) may be used outdoors. From the table it becomes clear that the annual yield from a Guadua plantation, transformed into cubic meters SWB is competitive to modified softwood (but has a hardness and density which is considerably higher), and is almost two times as high compared to baby Teak and over four times higher than regular Teak. In the case of a Moso plantation the annual yield in cubic meters of SWB is around half the annual yield of modified softwood, but at a similar level as baby Teak, and over twice as high as regular Teak.

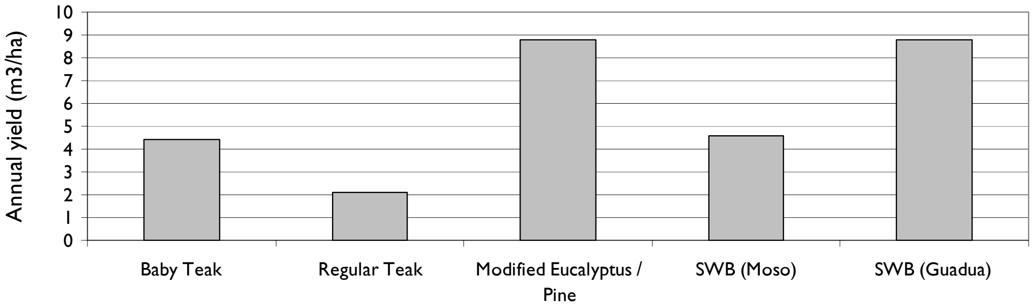

Figure 3.5: Estimates of the annual yield per hectare in cubic meters of bamboo- and wood based materials sourced from plantations apt for outside use

In figure 3.6 the annual yield of a bamboo or wood based plantation processed into B-quality materials (in this case MDF) is depicted. In practice for MDF production based on wood only fast growing softwood species will be used due to the relative low value added character of the material. The figure shows that Moso based MDF has an annual yield which is around half the yield of fast growing softwoods such as Eucalyptus and Radiata Pine, while Guadua based MDF is competitive in annual yields with MDF based on fast growing softwood. Note that the density of Radiata Pine and Eucalyptus (500 kg/m3) is lower than the density for bamboo (700 kg/m3). Taking into account a similar compression rate (factor 1.5) the bamboo based MDF will have a higher density (1050 kg/m3), and possibly better mechanical properties, than softwood based MDF (750 kg/m3).

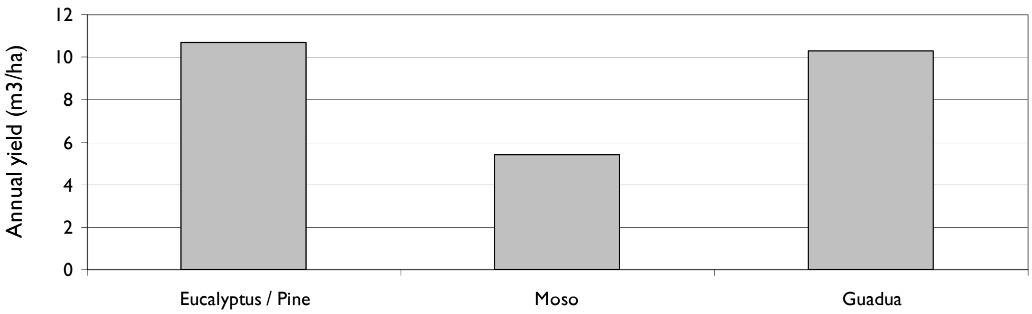

Figure 3.6: Estimates of the annual yield per hectare in cubic meters of bamboo- and wood based MDF sourced from plantations

Note that due to the comparison in annual yield in cubic meters, the bamboo stem was not integrated in the annual yield comparison because of its form. However, if a bamboo stem can substitute a solid wooden beam (see for example the FU walking bridge in the box in section 2.4) then a hectare of bamboo plantation can meet the demands of more FUs than a wood plantation. For example, if the 417 high quality stems harvested annually from a Guadua plantation are used in construction, and thus substitute a 0.05 x 0.1 x 8 m (0.04m3) long wooden beam each, they substitute 417 x 0.04 = 16.7 m3 of wooden material, which alone (not taking into account what happens with the other 417 lower quality stems from the Guadua plantation) is an amount which is twice as high as Guadua yields if processed into semi finished materials (see figure 3.6), showing the mechanical efficiency of the bamboo stem.

3.3 Conclusions & Discussion

The results in the previous section show that giant bamboo species such as Guadua may produce more cubic meters of semi finished material per hectare than all plantation grown hardwoods and most softwoods, and is only matched in annual yield by the fastest growing softwood species such as Eucalyptus and Radiata Pine. However, in general, (modified) softwoods (Eucalyptus, Pine, Poplar, etc.) have less aesthetic qualities and a lower hardness than hardwood alternatives, and are therefore to a larger extent used in applications where these properties are less required (e.g. for outdoor applications in markets such as garden wood and wall cladding). Therefore, in high end applications where hardness and aesthetic quality are of importance, such as flooring (indoors) and terrace decking (outdoors), SWB (also outdoors), taped mats and Plybamboo made from Guadua is the most efficient alternative in terms of annual yield. Moreover, also in the case of processing to B-quality materials, Guadua based MDF is competitive with the fastest growing softwood alternatives. No matter what the application is (either high end or low end) in which giant bamboo species such as Guadua are used, they are always competitive or better than wood alternatives in terms of annual yield, showing the potential of giant bamboo species for the future. However, currently almost all A-quality bamboo materials consumed in the West derive from China and are based on Moso bamboo. Due to the lower annual yield (around half of Guadua), Moso based bamboo materials have a lower annual yield compared to the fastest growing softwoods, but an annual yield which is competitive to the fastest growing hardwood species and more than twice as high as many other commonly used hardwood species (e.g. European Oak, regular Teak) in high end applications.

Due to the increasing pressure on our resources, it is important to use the hectares of land available globally in an increasingly efficient manner. Since humanity requires different resources for different needs (cropland for food, forests for materials, etc.) in combination with the increasing deforestation, it may be of importance to reforest degraded land in the future with a crop with high yields. In this chapter it was found that for the production of materials used as input in the interior decoration and building industry, bamboo may be the best alternative in terms of annual yield. The most interesting fact is that due to the combination of a relative high hardness and strength (like hardwood) and high growing speed (like softwood), one and the same giant bamboo species may be converted into both A-quality materials that can compete in high end markets with the highest quality tropical hardwoods (e.g. SWB with Teak) and B-quality materials that may be used in low end markets (e.g. MDF). For both markets bamboo is competitive or scores better in annual yield. This supports the proposition posed in section 1.4 that "bamboo grows faster than softwood but has hardwood properties." Furthermore, due to its long fiber bundles and specific mechanical and physical properties, bamboo may be converted into additional semi finished materials with certain competitive advantages over wood (e.g. use of BMB for the production of corrugated sheets; see box in section 2.7). This multi-functionality of bamboo is very different from wood, for which each application requires a specific species (e.g. tropical hardwood for decking outside, fast growing softwood for MDF production, etc.). Due to this versatility bamboo has a higher flexibility to meet possible shifts in demands for resources by different industries, and may prove to be the ideal reforestation crop for the future.

Some additional remarks are required at this point. In section 1.2 it was found that in order to fill the gap between demand (biocapacity) and supply (Ecological Footprint), demand should be diminished (e.g. lower consumption and footprint capacity) while supply should be increased (see figure 3.7 below).
First of all, as found in this chapter, bamboo may play a role by increasing the supply of raw materials through the high annual yield per hectare (high bioproductivity). A second benefit of bamboo as a resource is that it can thrive on pieces of land where wood may not (e.g. degraded land on slopes, see figure 1.10), and due to its extensive root network may help to prevent erosion and facilitate the restoration of a healthy water table (Billing and Gerger 1990, Tewari and Kumar 1998), potentially diminishing the environmental effects of erosion, landscape deterioration and desiccation relating to the environmental problem of ecosystem deterioration (see table 1.1). The features mentioned above make some bamboo species very suitable for reforestation of deserted land which is not useful (anymore) as agricultural land (e.g. over exploited land created by the clear cutting of tropical rain forests). Therefore, bamboo in the future may be able to increase the biocapacity by simultaneously increasing the area of fertile global hectares that is able to supply resources (see figure 3.7).

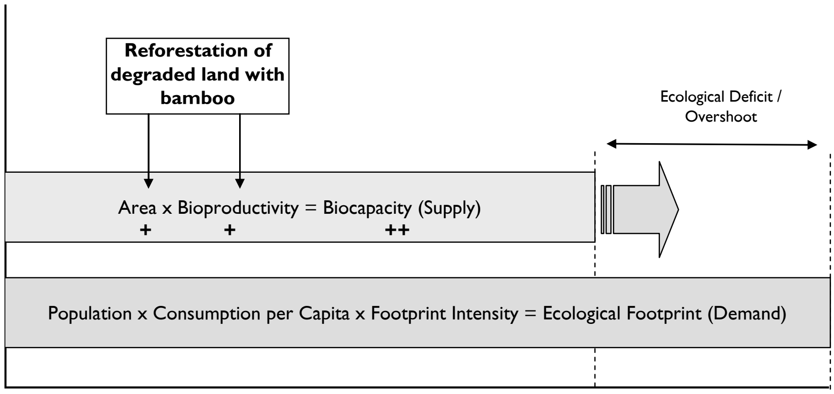

Figure 3.7: Gap between supply and demand between Biocapacity and Ecological Footprint and the potential role of bamboo at the supply side (figure adapted after WWF International 2006)

A final benefit of bamboo as a reforesting crop compared to wood is the low establishment time of a bamboo plantation. While the establishment time of a plantation of tropical giant bamboo species such as Guadua to come to maturity will not take longer than 10 years (Suarez 2006) and can be even less (see figure 3.8), the establishment time of a wood plantation to maturity may range from 15 years (Eucalyptus), 30 years (baby Teak), 70 years (regular Teak) to 80 years (European Oak) (Kuiper 2006, van Straten 2006). This means that a bamboo plantation will be able to deliver the annual yield of a mature plantation faster than any wood species can.

Figure 3.8: 3-year old plantation of Dendrocalamus Asper in Ecuador

Although the focus in the annual yield comparison was on the utilization of bamboo in the interior decoration and building industry, bamboo is also suitable as input in other high resource consuming industries such as the paper, biofuel, composite or textile industries, further highlighting the versatility of bamboo (e.g. wood is not suitable for the production of textile).

Figure 3.9: The bamboo micro fiber is increasingly being used in textile, such as in these socks

In the box below the annual yield of bamboo is compared with wood for the production of pulp (as input in paper) and biofuel. The results show that due to the fact that also younger bamboo stems can be harvested, annual thinning and therefore harvesting volumes may double for these kinds of applications, making the annual yield of bamboo compared to wood even higher, showing the high potential of bamboo in terms of annual yield for these industries as well.

Box: Annual Yield of Bamboo for Use in the Paper or Biofuel Industry

For pulp production, used as input in paper, logs (wood) or debranched and topped stems (bamboo) are processed by shredders to sawdust and fibers (additional 10% material loss assumed for both wood and bamboo). Since only cellulosic materials are required for pulp production, through mechanical pulping (pulping yield of approximately 90%, but lower quality) or chemical pulping (pulping yield of approximately 50%, but higher quality) non-useful components (e.g. lignin) are removed. Since bamboo and wood have a similar chemical composition pulp yields for both resources are similar (Dhamodaran et al. 2003).

In the case of pulp production for paper the annual yields per hectare for bamboo may be even higher than for the building and interior decoration industry since bamboo used for paper does not have to be mature (4-6 years old); rather, depending on the species it should be harvested at age 1 (Bambusa Vulgaris) or age 2 (Moso) (Dhamodaran et al. 2003), facilitating a yield per hectare that is twice as high as for the production of semi finished materials.

For paper the fiber characteristics determine the quality of the paper. Dhamodaran et al. (2003) provide an overview of bamboo species suitable for paper production, of which Bambusa Vulgaris seems one of the most promising species, although giant species such as Moso and various subspecies of Dendrocalamus (including Giganteus and Asper) are also reported. Due to its coarse fibers Guadua is not expected to be useful as input in the paper industry. Therefore, for the annual yield comparison besides Moso, Dendrocalamus Asper is included in the comparison. For Dendrocalamus Asper the annual yields of Guadua are adopted, since both are clumping tropical giant bamboo species.

Since unlike bamboo, trees do not acquire their full length in their first year, but grow and expand in size gradually, harvesting young trees does not result in higher yields per hectare. Eucalyptus is the most commonly known wood species used for paper production and was chosen as the representative wood species for the comparison. In figure 3.10 the annual yields in terms of cubic meters of wood based and bamboo based fibers/saw dust, used as input in the pulping process, are depicted. The annual yield for Moso is based on a yield of 1500 (2x 750) stems/ha x 0.0136 m3 (see table 3.3) x 90% efficiency = 18.36 m3. The annual yield for Dendrocalamus Asper is based on a yield of 1666 (2 x 833) stems/ha x 0.0235 m3 x 90% efficiency = 35.2 m3. The annual yield for Eucalyptus is based on the annual yield in logs (20 m3) x 90% efficiency = 18 m3. Note that in the comparison it is assumed that the yield is determined by the amount of cubic meters fibers/saw dust that can be produced, and not by the weight. Due to the higher density of bamboo this will result in heavier paper.

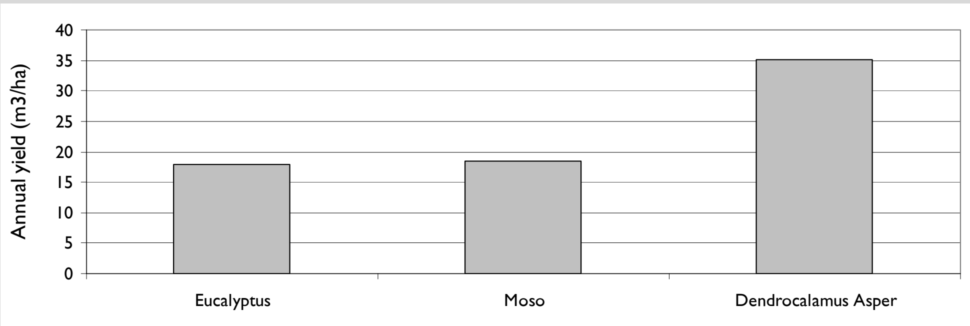

Figure 3.10: Annual yield of material sourced from a bamboo- and a wood plantation suitable for pulp production

Figure 3.10 shows that the for pulp production the annual yield of even subtropical bamboo species such as Moso is competitive with the fastest growing wood species Eucalyptus. If giant tropical bamboos such as Dendrocalamus Asper are used for pulp production, the annual yield for pulp production may be twice as high. Since the cellulose fibers in pulp may also be used as input in the textile or composite industry (although different processes are required), figure 3.10 shows the high potential of bamboo in terms of annual yield in these industries as well.

For biofuel production (e.g. biocoal) instead of calculating in volume (cubic meters), the total dry weight that can be produced annually from a plantation should be used as a base of comparison. Due to the relative high density this is an additional advantage for bamboo in this application compared to softwoods. According to Liese (personal communication, November 2008), young stems obtain their energy from older stems and their rhizomes of the same bamboo stand. To keep this cycle intact, including the vitality of the stand, a young stem should not be cut before it is 2-3 years old in order to store the energy for new stems in the future.

For the annual yield calculation for biofuel production was calculated with the dry weight of a mature Moso and Guadua stem (see table 3.3 and 3.4) multiplied by 1.25 to also take the biomass of branches, leaves and the top part of each stem into account. Rhizomes (in which also a considerable amount of biomass is stored) are excluded from this calculation since they are difficult to extract and may still be required as energy source for new shoots. As we saw above in section 3.2 a typical Moso plantation houses 3000 stems, which leads to an annual yield of 1500 stems when cut at two years old. Since Guadua plantations store around 5000 stems, they could provide an annual yield of 2500 two year old stems for use as biofuel. For this low added value application for wood Eucalyptus may be used as relevant alternative for the annual yield calculation.

In figure 3.11 the annual yields in terms of dry tons of wood and bamboo biomass for biofuel are depicted. The annual yield for Moso is based on a yield of 1500 stems/ha x 9.52 kg per debranched stem x 1.25 to include additional biomass in form of branches and leaves = 17.9 dry tons. The annual yield for Guadua is based on a yield of 2500 stems/ha x 16.43 kg x 1.25 = 51.3 dry tons. The annual yield for Eucalyptus is based on the annual increase in standing volume (25 m3) x 500 kg/m3 = 12.5 dry tons.

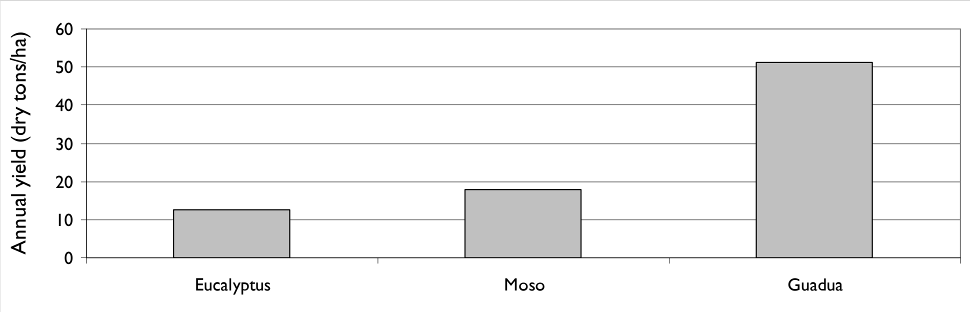

Figure 3.11: Annual yield of biomass available as input for biofuel

Figure 3.11 shows that due to the higher density of bamboo compared to softwood, the annual yield in terms of dry tons per hectare for both Moso and especially Guadua is considerably higher than even the fastest growing wood species. Since the energy value of bamboo has been reported in the range of 16 to 20 MJ/kg (El Bassam 1998, Misra and Dash 2000, Gielis, Kleinhardt-FGI 2002, Scurlock et al. 2000) it is on a similar level as the energy content of woody biomass at 17Mj/kg (El Bassam 1998). The above reveals the enormous potential of giant bamboos for the production of biofuels.

Although the high biomass production of bamboo is indicative of carbon sequestration in durable products, carbon is also stored in the trees and stems (including the roots) that remain standing in a sustainably managed plantation. Since carbon sequestration is such an important issue at the moment, in appendix B a hypothetical calculation is executed in which is calculated how much carbon a permanent hectare of bamboo plantation sequesters compared to a wood plantation. Note that there is a lot of discussion if carbon sequestration by renewable resources should be taken into account since it is usually only a temporal solution. Chances are high that the carbon stored in a new planted forest will be released in the atmosphere at a later stage in the future when these wood resources (or the land on which they are standing) are felled or consumed. In the opinion of the authors better solutions are available to reduce carbon emissions, such as substituting fossil fuel based energy by energy based on sustainable sources (e.g. solar and wind energy).

4 Conclusions

The main research objective of this report was **to assess the environmental sustainability of various bamboo materials based on use in Western Europe, compared to commonly used material alternatives and in particular timber.**
The environmental sustainability of a product or material is determined in this report through the eco-costs (environmental impact) at the debit side (negative environmental effects caused by bamboo materials during their life cycle contributing to the main environmental problems reported in table 1.1) and the annual yield at the credit side (effects diminishing the main environmental problems), calculated in the previous chapters for bamboo and various alternatives.
In this chapter the overall environmental sustainability (eco-costs and annual yield) of the various bamboo materials assessed will be compared with alternatives in applications in the building and furniture sector in which the specific properties of bamboo can be utilized: bendability (Plybamboo, BMB), aesthetics (stem, Plybamboo, SWB) and durability outdoors (SWB) based on current use in Western Europe. Again it should be emphasized that the eco-costs calculation is based on LCA, which is a methodology still under development and full of assumptions and estimations, meaning that the environmental impact outcomes only function as a rough indicator.

After the comparison of the environmental sustainability for the Western European market, a similar comparison will be executed for bamboo materials used locally in bamboo producing countries, where also the price and mechanical properties (stem, BMB) may serve as an additional unique property of bamboo. Finally, based on the findings for the comparisons, the future potential of bamboo and wood for sustainable development will be reviewed in this chapter.

4.1 Current Use in Western Europe

In table 4.1 below the markets in which the various bamboo materials may be used, based on unique differentiating properties, are summarized. For each market a certain bamboo material is compared with suitable, mostly wood based, alternatives. Note that the target markets mentioned are exemplary; more markets may be suitable for each unique property. For the comparison of the environmental sustainability of bamboo to alternatives the following scale was used: - - very bad (eco-costs > twice as high; annual yield > twice as low), - bad (eco-costs 1.25 - 2 times as high; annual yield 1.25-2 times as low), +/- reasonable (eco-costs 0.75-1.25 times as low/high; annual yield 0.75-1.25 times as high/low), + good (eco-costs 1.25-2 times as low; annual yield 1.25-2 times as high), ++ very good (eco-costs > twice as low; annual yield > twice as high). For the annual yield component the figures for Guadua were also included as a hypothetical reference to evaluate the future potential of Guadua, since production of Guadua based semi finished materials is still very low. Furthermore, for the annual yield component was assumed that Beech (European hardwood) has a similar annual yield as European Oak, that Azobé has a similar yield as regular Teak, that the modified wood alternatives (Plato wood, acetylated wood) were based on Pine, and that plywood made from Pine has a similar annual yield in logs as Eucalyptus, but halved, due to the higher material losses of veneer production (thus calculating with 0.5 x 20m3 = 10 m3). Finally, the annual yield evaluation in table 4.1 and the remainder of this section is based on the total production of A-quality materials per hectare (see section 3.2). Only for SWB the annual yield component is based on a scenario in which the complete annual yield from a plantation is used as input in the SWB industry. Since the eco-costs and annual yield have a different scope (see table 1.5) and character, they cannot be added up one on one. However, together they do provide a good indication of the environmental sustainability of bamboo materials.

Table 4.1: The current environmental sustainability based on eco-costs and annual yield for various bamboo materials in suitable markets in Western Europe, compared to relevant alternatives

Unique feature	Bamboo material	Possible target market	Competing alternatives	Eco-costs compared to alternative	Annual yield (Moso) compared to alternative	Annual yield (Guadua) compared to alternative
Bendability	Plybamboo	Curved seatings (indoors)	European Beech	--	++	++
			Plywood & veneer	-	-/--	+/-
	BMB	3D molded seatings (indoors)	ABS	-/--	++[19]	++
Aesthetics	Stem	Chair, table, lamp component	European Oak	--	++	++
			Pine	--	++	++
			Teak (plantation)	-	++	++
			Teak (FSC certified)	++	++	++

[19] Since ABS (and Polypropylene used in Tech-Wood) is based on oil, it is not a renewable resource that can provide an annual yield. Therefore, the annual yield factor for ABS is negative compared to bamboo.

Aesthetics & hardness	Plybamboo	Tabletops, flooring	European Oak	--	++	++
			Teak (plantation)	-	++ (regular Teak), +/- (baby Teak)	++ (regular Teak) +/++ (baby Teak)
			Teak (FSC certified)	++	++ (regular Teak), +/- (baby Teak)	++ (regular Teak) +/++ (baby Teak)
			Plywood & veneer/top layer of hardwood	-	-/--	+/-
			MDF & veneer/top layer of hardwood	-	--	+/-
Aesthetics & outdoor durability	SWB	Decking	Teak (plantation)	--	++ (regular Teak), +/- (baby Teak)	++ (regular Teak) +/++ (baby Teak)
			Teak (FSC certified)	+	++ (regular Teak), +/- (baby Teak)	++ (regular Teak) +/++ (baby Teak)
			Teak (natural forest)	++	++ (regular Teak), +/- (baby Teak)	++ (regular Teak) +/++ (baby Teak)
			Azobé (plantation)	--	++	++
			Azobé (FSC certified)	+	++	++
			Azobé (natural forest)	++	++	++
			Plato wood	--	-/--	+/-
			Acetylated wood	--	-/--	+/-
			Tech-Wood	--	++ (see footnote 19)	++ (see footnote 19)

From table 4.1 the following conclusions can be drawn about the competitiveness of the various bamboo materials in terms of environmental sustainability (eco-costs + annual yield) based *on the current situation; state of the art Fall 2008* (therefore, based on bamboo materials made from Moso bamboo since Guadua based materials are not sufficiently available) and use in Western Europe.

Stem

In all applications where the bamboo stem may be used, European grown wood scores better in terms of eco-costs. Due to its efficiency in form and processing, and the high growing speed, in annual yield the stem scores significantly better than even the fastest growing softwood species (including all other bamboo materials). However, due to the irregular form and high transport costs, the market potential of the stem for mass applications in the West is limited which makes this high annual yield of limited use (which is not the case in bamboo producing countries; see section 4.2).

Plybamboo

In applications where Plybamboo is typically used (flooring, tabletops), it performs worse in terms of eco-costs than locally grown hardwood and wooden board materials (with hardwood top layer), and better than FSC certified tropical hardwood (Teak) and tropical hardwood derived from natural forests. In terms of annual yield Plybamboo performs better than almost all hardwoods (only baby Teak is competitive), but worse than MDF and Plywood based on fast growing softwood species. Therefore, from an environmental point of view, if Plybamboo is to be used in these applications in the West, it is recommended to use Plybamboo veneer on a local wood based carrier such as MDF (e.g. engineered flooring).

SWB

For outdoor applications most softwoods are not eligible due to their low durability, and tropical hardwood is often used. In high end applications (e.g. decking), SWB has higher eco-costs than suitable plantation grown tropical hardwood species such as Teak and Azobé. However, for tropical timber, including FSC certified timber, it is often not clear if the wood derives from a natural forest or a plantation (only 11% of productive forest area in the tropics), whereas demand for tropical hardwood is growing.[20] SWB scores significantly better in eco-costs than timber which is derived from natural tropical forests and FSC certified tropical hardwood. Therefore, if SWB can help replace tropical timber from natural forests (e.g. a portion of 64.6% of all FSC tropical timber derives from natural forests) it may be considered an environmental friendly alternative in terms of eco-costs, although far better performing wood based alternatives (e.g. Tech-Wood, Plato wood and acetylated wood) are available.

[20] This also shows the need to establish more plantations for tropical hardwood production.

Although the annual yield of baby Teak is competitive with Moso based SWB, SWB does have a higher annual yield than most other tropical hardwoods. Nevertheless, if wood modification (thermal modification, acetylation) is executed to fast growing species such as Radiata Pine, Moso based SWB scores worse in terms of annual yield than these alternatives.
It can be concluded that until the moment that these wood based alternatives have the production capacity and commercial validity to fully substitute the demand for (FSC certified) tropical hardwood, SWB can be deployed as a relatively environmental friendly alternative to help meet this demand, and help in the prevention of the clear cutting of tropical forests, perceived as important carbon sink.

Bamboo Mat Board (BMB)
Due to its specific characteristics BMB may be used in applications in which wood alternatives cannot (e.g. grid matrices, 3D bowls). However, in terms of eco-costs BMB scores worse than ABS in these kinds of applications, but better in terms of annual yield since ABS is based on finite resources (oil).

4.2 Current Use in Bamboo Producing Countries

In case the bamboo materials are used in applications in the bamboo producing countries themselves (in this case, China), the eco-costs of the various materials will be reduced due to lower eco-costs for transport. While the annual yield figures will remain the same, the eco-costs of Plybamboo will be reduced by 25-28% (depending on the color and structure), SWB by19.2% and the stem by 94.5%. Looking at the same markets as reviewed in table 4.1, in case of use in China, one can conclude that Plybamboo and SWB become increasingly competitive with locally grown wood species in terms of eco-costs (although most locally grown wood species due to a shorter production process will remain better). In combination with the often high annual yields, this makes the various industrial bamboo materials a competing alternative in terms of environmental sustainability compared to locally grown species, and even more if the production efficiency and application of less environmental harmful resins can be increased.

In the case of the bamboo stem, differences in eco-costs are especially high between use in China or in Western Europe due to the high space occupation during transport of the stem. Furthermore, due to the low costs, high local availability and lower input requirements for housing, furniture and household products compared to the Western European situation, the applicability and market potential for the stem is considerably higher in most bamboo producing countries. In these markets, due to the short production process, the bamboo stem becomes the most environmentally friendly alternative (both in terms of eco-costs and annual yield), even better than locally grown softwood alternatives (see for example the black bar in figures 2.12 and 2.14).

Since bamboo is especially available in China and India (millions of hectares of bamboo forest and plantations are available), where population and consumption is particularly increasing, and large areas of land are degraded, it is here where the bamboo stem can make the most advantage of its high bioproductivity and area use (see figure 3.7) to help meet local resource demand, especially for housing. For example, in China in the coming decade around 400 million new houses need to be built in the countryside (McDonough and Braungart 2002). In combination with earth or mud very strong, earthquake resistant low cost housing can be created based on bamboo (see figure 4.1). Due to the higher annual yield, this applies even more for housing made from giant bamboo species such as Guadua.

Figure 4.1: Low cost bamboo housing in Latin America
Note: in terms of durability the mud/mortar clad housing (right) is strongly preferred over the version in which all the bamboo is directly exposed to climatic circumstances (left)

Also other coarse materials such as BMB may have a higher applicability in resource consuming sectors such as the building industry, in bamboo producing countries themselves. Although compared to wood based materials (Plywood, MDF, chipboard, etc.) BMB scores worse in terms of eco-costs, if the competitive advantages of BMB compared to wood based materials are utilized (e.g. bendability), BMB might be the best alternative from the eco-costs point of view. For example, as seen in the box in section 2.7, BMB based on multi directional woven mats can be pressed into strong and cheap corrugated boards with good durability outdoors, which cannot be produced in the same manner as wood. Compared to other alternatives (steel, PVC) for low cost corrugated board, BMB is therefore the best alternative from an environmental point of view in bamboo producing countries (see also figure 2.24).

4.3 Future Use of Bamboo

If we look at our future needs, taking into account the increasing pressure on the environment and our remaining resources, how and where should bamboo be utilized as a renewable resource?

In terms of eco-costs it can be concluded that the further away the bamboo stem is industrially processed, the more artificial resins are added, and the further it is transported, the higher the eco-costs of the bamboo materials are, and the less competitive it becomes in eco-costs compared to locally grown wood alternatives. If the bamboo stem is used directly in appropriate applications in bamboo producing countries, it is the most environmentally friendly material around because of the very short production process; no wood species can be harvested and after drying be directly used without further processing. However, if the stem is industrially processed into boards and transported to Western Europe, this environmental edge compared to locally grown wood species is lost, and the various bamboo materials in general only score better than non plantation grown tropical hardwood timber (especially when sourced from natural forests). Therefore it is recommended to only use bamboo materials in small quantities in Western Europe in applications in which the specific competitive advantages of bamboo materials (e.g. hardness, bendability, aesthetic properties) are utilized, e.g. top layer of engineered flooring, veneer layer on tabletop with a MDF carrier.

Figure 4.2: In the ceiling of the new airport terminal in Madrid by Richard Rogers, the bendability of plybamboo laths is utilized

Nevertheless, although various bamboo materials used in Western Europe score worse from an environmental impact point of view than locally grown wood species, compared to various other materials, especially those based on finite resources (e.g. metals, plastics), the renewable character of bamboo makes it an environmentally sustainable alternative compared to many other materials, also when used in Western Europe.

In terms of annual yield it was found that the bamboo stem was the best performing renewable resource around if used as a semi finished material in a durable application (e.g. housing). In the case giant tropical bamboo species such as Guadua are used for the production of industrial materials (e.g. Plybamboo, SWB), they have a higher annual yield than all hardwood and almost all softwood alternatives; only wood based boards (MDF, Plywood) based on the fastest growing softwood species may perform slightly better in terms of annual yield. However, due to the higher processing efficiency and the even shorter harvesting time (1-2 years) the high annual yield of bamboo is utilized the best in pulp and fiber demanding industries, such as the paper-, textile- and composite industry.

Different resources are required for different needs (cropland for food, forests for materials, etc.). Due to the increasing pressure on the remaining hectares of land globally and the increasing deforestation, it may therefore be necessary to reforest degraded land in the future with a crop with high yields. The kind of crop required may depend on the highest needs and priorities locally.

In (sub)tropical areas in most cases giant bamboo species such as Guadua will be the ideal contender, not only because it can be planted on land which is difficult to reforest with wood and has a very short establishment time compared to wood, but also because it combines a high annual yield with a large versatility. In the building- and interior decoration industry depending on which semi finished material it is transformed into, bamboo may be deployed in the most demanding high end applications but also in low-cost low-end applications, and still be competitive. If transformed into pulp or fibers, the same giant bamboo species may also be used for the production of paper, textile or natural fiber reinforced composites. Furthermore, various bamboo species can also be used for biofuel and even as food (young bamboo shoots), further highlighting the versatility of bamboo compared to wood.[21] Above, it was found that the applicability of especially B-quality bamboo materials (including the stem) may be higher in the bamboo producing countries. Taking into account the increasing consumption patterns and the population growth in the main bamboo producing countries of India and China, bamboo should first be deployed as a tool toward a sustainable society in the countries where it grows, and not be transported over thousands of kilometers to Western markets where local grown renewable resources may perform better in terms of eco-costs. However, if demand cannot be met by local sources, due to its versatility and high annual yields, bamboo is the best alternative to help meet this demand from an environmental perspective, especially if it can be sourced from a closer distance in the future (e.g. from Africa for Europe, and from Latin America for North America) which should be further stimulated in the future by the establishment of additional bamboo production nuclei in the future.

[21] A nice overview of applications in which bamboo is used is provided in *The Book of Bamboo* (Farrely 1984)

5 Discussion & Recommendations

It is the authors' hope that through the environmental sustainability assessments executed in this report understanding is created amongst stakeholders in the bamboo industry that bamboo materials are not always - as often unfoundedly claimed - the best environmental benign alternative around. This is only the case when several parameters, as presented in this report, are met.

Especially the eco-costs calculations can help pinpoint the steps in the production process that are most harmful from environmental point of view, based on which directed action can be taken by bamboo material producers to make the process more environmental friendly. This was also shown for the current eco-costs evaluation executed for the bamboo material importer Moso International. For example, as a result of the findings in this research, Moso International is trying to convince the material producer to avoid the unnecessary second drying cycle for carbonized Plybamboo (see appendix A).

Taking the above into account, the following recommendations can be made to increase knowledge about the preconditions under which bamboo resources can be considered the best environmental benign alternative in the future.

LCA Based Research for Bamboo

To get a better understanding of the environmental impact of bamboo much more LCA based research should be executed for different production to consumption scenarios based on:

- Different countries and factories based on different technology levels of production sites (manual, semi industrial, industrial facilities).
- Different countries of consumption, with a larger emphasis on the environmental competitiveness of bamboo when used locally, in bamboo producing countries.
- Different FUs with a broader base of comparison.
- Different bamboo based materials and fabrics, and especially the use of bamboo fibers for the production of:
  - Natural fiber based composites, preferably in combination with an environmentally friendly biodegradable resin (e.g. PLA);
  - Pulp for paper and cardboard production;
  - Bamboo textile, which is a new hype in Western countries as a presumably eco-friendly alternative. However, taking into account the findings in this report, and the knowledge that the production of bamboo fibers apt for textile follows a lengthy industrial process similar to the production of viscose, also the eco "friendliness" of bamboo textile in terms of eco-costs may be questioned.
- Different life cycle scenarios in which also the maintenance and end-of-life scenario is taken into account, including the potential use of disposed bamboo- and wood based materials for energy production, and the consequences for the eco-costs calculation (potential deduction because of the prevention of an additional amount of fossil fuel being consumed).

Annual Yield Research for Bamboo

To get a better understanding of annual yield (indirectly also carbon sequestration) by bamboo resources compared to wood, it is recommended:

- To execute similar annual yield calculations for other giant bamboo species such as *Dendrocalamus Asper or Giganteus*, including the applications in which they may be used.
- To execute annual yield calculations for the production of the bamboo fiber for the development of natural fiber reinforced composites, including the appropriate age required for the input material. It is likely that younger stems may be used as input for this material resulting in a yield that may be up to 2-3 times higher as for the production of other semi finished bamboo materials such as Plybamboo.
- To execute additional or new annual yield calculations for bamboo species apt for other resource demanding markets such as for textile, paper, biofuel or charcoal (also based on their appropriate felling age, see directly above), compared to suitable wood or other plant species for this application. For biofuel calculations more research should be executed to determine the optimal harvesting cycles and planting grids for various bamboo species with the highest caloric value in order to establish production regimes with highest annual yield in GJ per hectare.
- To execute the annual yield calculation again in various parts in the world with different geographical, climatic and soil conditions (e.g. temperate versus tropical climate, fertile versus infertile land, etc.), calculating with various local species of bamboo and wood that seem most suitable to use under the specific circumstances of the selected site.
- To execute new annual yield calculations based on future consumption scenarios and the role reforestation by bamboo may play in meeting growing resource demands.

Recommendations for the Bamboo Industry

In order to improve the environmental sustainability of their products, industrial bamboo material producers are recommended:

- To execute similar environmental impact assessments as the ones executed in chapter 2 in order to better understand which steps in the production process are most harmful to the environment and should therefore receive priority if the environmental impact of the materials is to be reduced (see for example figure 2.2). For example, industrial bamboo producers could use less harmful additives during the production process of their materials (e.g. preservatives, resins), either by reducing the amount of resins and chemicals used, but preferably by opting for more environmental friendly or biodegradable resins and chemicals.

- To make their materials lighter. For example, Tech-Wood (see section 2.6)saves a lot of material by extruding profiles instead of making a solid product.
- To develop take-back procedures, and recycling processes in which the materials at the end of their lifetime are 100% reusable in the same function (Cradle to Cradle strategy).
- To further increase the efficiency of the transformation process of the bamboo resource in semi finished materials, including the search for more high end and durable materials and applications in which the rest material can be used (e.g. similar to Tech-Wood panels).
- To increase the establishment of plantations of high yielding giant bamboo species suitable for the production of fibers and materials.
- To further develop new industrial bamboo materials, like corrugated BMB boards, in which the competitive advantages and specific differences of bamboo compared to wood are utilized. For example, if the bamboo micro fiber is chosen in natural fiber based composites because of its mechanical performance, it might be worthwhile to do research into processes to extract bamboo fibers in an efficient and environmentally friendly way from the stem, including space efficient ways of transportation to the composite material production site (e.g. compressed bags through vacuum suction).

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Appendix A: Environmental Assessment of Bamboo Materials

In this appendix the complete data processing for the environmental impact assessment of one bamboo material (3-layer bleached Plybamboo board) is presented (for conclusions see chapter 2). For various other bamboo materials (1-layer Plybamboo board and -veneer, bamboo stem, and Strand Woven Bamboo) the environmental effect of all activities in the production chain was (partly) based on the calculation for 3-layer bleached Plybamboo board, and therefore presented in a more compressed manner in this appendix.

General Points of Departure for Calculation

Production site: Plantation and first processing in the Anji region, final processing in Huangzhou, both in the province of Zhejiang, China.
Consumption site: Warehouse of Moso International b.v. in Zwaag, the Netherlands
Time period of data collection: July 2007
Resource: *Phyllostachys Pubescens* (Moso)
- Density: 700 kg/m3 (dry state)
- Length: up to 15 m
- Diameter: 10-12 cm on the ground, tapering to the top
- Wall thickness: 9 mm at bottom of stem, tapering to the top

Data suppliers:
[1] DMVP and Dasso (Plybamboo board and veneer producers in Huangzhou, China), Mr. Xia
[2] Moso International (bamboo board importer), Mr. René Zaal (director)
[3] Pablo van der Lugt, based on visits to various bamboo factories in the Anji region, China, March 2006
[4] Huangzhou Dazhuang Floor Co., Ms Isabel Chen

Further data was derived from a previous study executed by the first author based on the TWIN 2002 model:
[5] van der Lugt, P., van den Dobbelsteen, A. and Abrahams, R. 2003. Bamboo as a building material alternative for Western Europe? A study of the environmental performance, costs and bottlenecks of the use of bamboo (products) in Western Europe. *Journal of Bamboo and Rattan* 2(3): 205-223.

Since all bamboo materials evaluated during this environmental impact assessment are derived from China, it is important to understand that the Chinese bamboo industry is very efficiently organized; almost every part of the resource (bamboo stem) is used for a certain product. The central dimension for most industrial bamboo materials is 2.66 meters, based on which the complete Chinese industrial bamboo industry is synchronized. Usually about 8 meters (3 x 2.66 m) of a harvested Moso stem will be used for the development of bamboo products. The bottom two parts of 2.66 meters are mostly used as input for the manufacturing of industrial bamboo materials such as Plybamboo boards, while the upper part may be used for smaller bamboo products such as blinds and chopsticks [2, 3]. For the Plybamboo industry the bottom segments of the stem will first be processed into rough strips (approximately 2630 x 23 x 8 mm) and then in fine planed strips (2500 x 20 x 5 mm) that end up in the final product [1]. According to [1, 2], per stem part (2.66 m), 12 rough strips can be made from the bottom part of the stem. Due to the smaller diameter only 8 rough strips can be derived from the second segment of the stem, making an average of 10 strips per stem part for the lower two parts of the stem (bottom and middle segment).
The dimension of 2.66 meters was chosen because it provides tolerance for failure for the production of Plybamboo boards, which is usually based on the international standard of 1.22 x 2.44 m. For this reason the Functional Units (FUs) chosen for the environmental impact assessment of the various bamboo materials in this research were based on these dimensions as well. Please note that the FU mentioned in this appendix is only used to establish the eco-costs/kg of the various bamboo materials based on a standard element. In chapter 2 other FUs are established to assess the eco-costs of bamboo compared to wood in various relevant applications.

Bleached Plybamboo board (3-layer)

General Data

Product: Bleached 3-layer Plybamboo (consisting of two layers of 5 mm plain pressed Plybamboo at the outsides, and one layer of 10 mm side pressed Plybamboo in the core).

The 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), in which 244 fine planed strips (2500 x 20 x 5 mm) are used [1].

Full Production Process (Cradle to Site)

1. Harvesting of bamboo on sustainably managed plantations
2. Transport from plantation to strip manufacturing facility
3. Strip making
4. Transport from strip manufacturing facility to factory
5. Rough planing
6. Strip selection
7. Preservation & coloring: bleaching
8. Drying
9. Fine planing
10. Strip selection
11. Glue application
12. Pressing strips to 1-layer board
13. Sanding 1-layer board
14. Glue application
15. Pressing three layers to one board
16. Sawing
17. Sanding 3-layer board
18. Dust absorption (during all steps)
19. Transport from factory to harbor
20. Transport from harbor to harbor
21. Transport from harbor to warehouse

To calculate energy consumption back to the FU it is important to understand how many strips are necessary to produce one board. In the final board 244 strips are used. Due to energy consumption allocation the strips that do not end up in the final product also need to be taken into account for the calculation. According to [1], during the production process there are two selection rounds (after rough planing and fine planing) where strips that do not meet quality standards are discarded (and used as bio fuel). In each round 6% of the strips are discarded. This means that at the beginning of the production process 12% more strips than the 244 strips in the final product were processed, which results in 277 strips. As was explained above, per stem part of 2.66 m, 10 rough strips can be derived, meaning that 277/10 = 27.7 stem pieces of 2.66 m are required per FU.

Determination of Input Data per Process Step

1. Harvesting of bamboo on sustainably managed plantations


In the calculation it is assumed that no fertilizers and pesticides were used on the plantations from which the stems were extracted. Harvesting figures are based on [5], in which is estimated that 234 stems can be harvested with chain saws on one gallon (3.785 liters) of gasoline, which comes down to 0.016 liters of gasoline per stem. Since for one FU 27.7 stem segments of 2.66 m are required, 27.7/2 = 13.85 stems are required per FU (taking into account that per 8 m stem only the bottom two parts of the stem can be used for Plybamboo board production). This means that per FU: 13.85 × 0.016 = 0.224 liters of gasoline are consumed.

Input in LCA: Cultivation of bamboo on a sustainably managed plantation

Gasoline consumption	0.224 liters/FU

2. Transport from plantation to strip manufacturing facility


It is important to understand that in the Eco-costs method the environmental burden of transport is based on the kind of transport vehicle (boat, 5-ton truck, 24-ton truck, etc.), the efficiency of packing (how many FUs can be transported per transport load), and the number of kilometers of the journey (usually based on a 50% payload, i.e. empty return of the containers). The weight of the load itself is integrated in the earlier mentioned parameters, based on average transport loads.[22]

According to [1] an average of around 320 stems with a length of 8 meters are transported per truck load with a 5-ton truck over a distance of 15 kilometers [2], which results in 320 stems/13.85 stems per FU (see step 1) = 23.1 FUs being transported per truckload. For small trucks the eco-costs are usually calculated based on the eco-costs per km of a certain vehicle, based on an empty truckload for the return (thus calculating with 2 x 15 = 30 km).

Input in LCA: Transport plantation to strip manufacturing facility

Distance	30 km
Kind of transport	5-ton truck
Amount of FU per load	23.1 boards (FU)

[22] Only for very low weight loads (under 400 kg/m3) the volume should be integrated in the eco-costs (Vogtländer 2008), which was done for sea transport of bamboo stems (see later in this appendix).

3. Strip making



According to [1], 9000 strips can be produced in 8 hours with the strip making machine (5.5 kW), which corresponds to 1125 strips per hour, which corresponds to 1125 strips/277 strips per FU = 4.06 FU (boards)/hour. It takes 1/ 4.06 = 0.25 hour to produce one FU. Energy consumption per FU is then 0.25 hour x 5.5 kW = 1.38 kWh/FU

Input in LCA: Strip making

Energy consumption/FU	**1.38 kWh/FU**

4. Transport from strip manufacturing facility to factory

According to [1, 2] 8 tons of strips are transported per truckload (10-ton truck) from the strip processing facility to the factory in Huangzhou, over 300 kilometers.[23] One rough strip weighs approximately: 2.6 x 0.023 x 0.009 m = 0.00054m3 x 700 kg/m3 = 0.38 kg per strip. Per truckload 8000/0.38 = 21052 strips of 2.6 m long are transported, resulting in 21052 strips/277 strips per FU = 77.6 FUs per truckload. For small trucks the eco-costs are usually calculated based on the eco-costs per km of a certain vehicle, based on an empty truckload for the return (thus calculating with 2 x 300 = 600 km).

Input in LCA: Transport from strip manufacturing facility to factory

Distance	**600 km**
Kind of transport	**10-ton truck**
Amount of FU per load	**77.6 boards (FU)**

5. Rough planing


According to [1], 4500 strips can be produced in 8 hours with the rough planer (15-20kW), which corresponds to 562 strips per hour, which corresponds to 562 strips/277 strips per FU = 2.03 FUs (boards)/hour. It takes 1/2.03 = 0.49 hour to produce one FU. Energy consumption per FU is then 0.49 hour x 17.5 kW = 8.62 kWh/FU.

Input in LCA: Rough Planing

Energy consumption/FU	**8.62 kWh/FU**

6. Strip selection

According to [1], after quality control, 6% of the strips will be discarded and burnt in the oven. This means that after this process step 277 - 6% = 260 strips are needed for the final product, which consists of 244 strips (another 6% will be lost in

[23] Note that this is a very factory dependent calculation; some bamboo factories located near the harbor of Ningbo, China, have bamboo plantations next to the factory.

the second strip selection after fine planing in step 9 below). Because of energy consumption allocation also the strips that do not end up in the final product need to be taken into account.

7. Preservation & coloring: bleaching

Preservation and coloring take place at the same time and can be performed by either bleaching or carbonizing the strips. In this case the bleaching process is analyzed (the carbonizing process is analyzed later in this appendix).

Addition of chemical substances

According to [1], the bamboo strips are bleached by "cooking" them for 4 hours in a boiling pool in a H_2O_2 solution at 70-80 degrees Celsius. After the first round additional H_2O_2 will be added for the second round of strips to be bleached. After this round, the solution cannot be used again and is settled through chemical treatment.

For H_2O_2 consumption per FU the following calculation can be made, based on the figures provided by [1]. Per 8 hours 3000 strips are bleached (two rounds of 4 hours). This corresponds to 3000/260 = 11.53 FUs. Per day (8 hours), 120 kg H_2O_2 solution (27% concentration) is used (80 kg for the first round, 40 kg added for the second round), which corresponds to 0.27 x 120 kg = 32.4 kg H_2O_2. Per FU H_2O_2 consumption is then 32.4/11.53 = 2.81 kg H_2O_2. Since the eco-costs / kg data are provided for a 50% solution in water, for the LCA input is calculated with 2.81 x 2 = 5.62 kg H_2O_2 50% solution per FU.

Input in LCA: H_2O_2 addition for bleaching

Added H_2O_2 per FU	**5.62 kg H_2O_2 solution/FU**

Energy consumption

The boiling pool is heated through the use of a 2-ton boiler. Strips required for the production of 11.53 FUs are bleached each day (8 hours). This corresponds to 11.53/8 = 1.44 FU per hour, which corresponds to 1/ 1.44 = 0.69 hour per FU, and therefore an energy consumption of 2.3 kW (boiler, see box below) x 0.69 = 1.59 kWh/FU.

Box: Energy Consumption by the 2-ton Boiler (22kW)

The steam produced by the boiler is used for various machines in the factory (drying chamber, hot presses, boiling pool, carbonization). Sometimes the heat from the boiler goes to various machines, sometimes only to one. However, in this calculation it is assumed that all machines connected to the boiler are running at the same time. It is difficult to estimate how much energy from the boiler each machine uses; however, the temperature required for each process step is expected to be an important indicator. According to [1] the drying chamber requires steam (evaporated water) at a temperature of 50-60 degrees Celsius, the boiling pool at 70-80 degrees Celsius, while the carbonization kettle will require 120-130 degrees Celsius. The temperature of the water required by the press is unknown but will probably be in the same line as the carbonization kettle, since it is based on steam. If the energy consumption of each machine sourced by the boiler (drying chamber, hot press, boiling pool, carbonization kettle) is based on the

temperatures used, then the energy distribution is as follows: drying chamber : boiling pool : hot presses : carbonization = 1 : 1.4 : 2.4 : 2.4. According to [1] there are two boiling pools, two carbonization kettles and two one-layer hot presses in the factory. All these machines are attached to the boiler so the number of machines also has to be taken into account for the energy distribution:
Drying chamber : boiling pool : hot presses : carbonization = 1 : 2.8 (1.4 x 2) : 4.8 (2.4 x 2) : 4.8 (2.4 x 2).

Based on these ratios the division of the capacity of the boiler (22 kW) can be divided over the various machines:
Drying chamber: 22 x 1/13.4 (= 1 + 2.4 + 4.8 + 4.8) = 1.64 kW.
Boiling pools: 22 x 2.8/13.4 = 4.59 kW for two pools, and 2.3 kW for one pool.
Hot presses: 22 x 4.8/13.4 = 7.88 kW for two presses, and 3.94 kW for one press.
Carbonization kettles: 22 x 4.8/13.4 = 7.88 kW for two kettles, and 3.94 kW for one kettle.

Besides electricity, the boiler consumes 400 kg sawdust per hour [1], which is sourced from waste produced in the other process steps.

Input in LCA: Energy consumption for bleaching

Energy consumption/FU	**1.59 kWh/FU**

8. Drying

After bleaching, the strips are dried in a drying chamber. Besides the energy consumption of the drying chamber itself (15kW), steam is used in the drying chamber produced by the boiler (1.64 kW, see box before). According to [1], the drying room is able to dry 30,000 strips at once. The drying times for bleached strips are different from those for carbonized strips. Bleached strips require a 72-hour drying cycle. This means that 30,000/260 = 115.4 FUs can be dried in one cycle, corresponding to 115.4/72 = 1.60 FU/hour, which corresponds to 1/1.6 = 0.625 hour/FU. Energy consumption per FU is then 15 (drying chamber) + 1.64 (boiler) = 16.64 Kwh x 0.625 = 10.4 kWh/FU

Input in LCA: Drying bleached strips

Energy consumption/FU	**10.4 kWh/FU**

9. Fine planing

According to [1], 38-40 meters of strips can be processed per minute by the fine planer (20 kW). The strips are 2.63 meters long, which corresponds to 15 strips per minute, which corresponds to 900 strips per hour, which corresponds to 900 strips/260 strips per FU = 3.46 FUs (boards)/hour. It takes 1/3.46 = 0.29 hour to produce one FU. Energy consumption per FU is then 0.29 hour x 20 kW = 5.8 kWh/FU.

Input in LCA: Fine planing

Energy consumption/FU	**5.8 kWh/FU**

10. Strip selection

According to [1], after selection, 6% of the strips will be discarded and burnt in the oven. This means that after this process step 260 - 6% = 244 strips will end up in the final product.

11. Glue application (1-layer boards)

According to [1], glue consumption for making 1-layer plain pressed bamboo boards of 5 mm thick is 50 grams urea formaldehyde[24] per m2 in wet condition. The kind of urea formaldehyde glue used complies with the European E1 norm [2]. Since for each 3-layer bamboo board, two 1-layer plain pressed boards are used, this figure needs to be doubled to 100 grams per m2.

For the development of a 1-layer side pressed 10 mm thick board, eventually used in the middle of the 3-layer board, 4 x 50 = 200 grams glue/m2 is consumed, since the thickness of the strips (and therefore the glue surface) measures 10 mm per strip instead of 5 mm, while there are twice as many strips used. The total glue consumption (in wet conditions) for making the three separate boards is then 300 g/m2, which corresponds to 300 x 2.98 m2 = 894 grams per FU (board) in wet conditions.

Input in LCA: Glue application (1-layer boards)

Type of glue	Urea formaldehyde complying with E1 norm
Weight/amount of glue	894 grams per FU (wet state)

12. Pressing strips to 1-layer board

After glue application the strips are processed into 1-layer boards using hot presses. Besides the energy consumption of the press (5.5kW), steam from the boiler is required. Energy consumption of the boiler that can be allocated to the hot presses is 3.94 kW per machine (see box above).

According to [1], 350 m2 board can be processed per day (8 hours), corresponding to 43.75 m2 per hour. Each FU consists of three layers (two 1-layer plain pressed boards of 5 mm thickness and one 1-layer side pressed board of 10 mm thickness; for this calculation it is assumed that their processing time at the press is the same), which means that in the final product three 1-layer boards are required. This means 43.75/3 = 14.58 m2 of 3-layer board can be produced per hour based on the various 1-layer boards. This corresponds to 14.58/2.98 (m2 per board) = 4.89 FU/hour, which corresponds to 0.20 hour/FU. Energy consumption per FU is then 0.20 hour x (5.5 + 3.94)kW = 1.89 kWh/FU.

Input in LCA: Pressing strips to 1-layer board

[24] Note that depending on the final application in which the Plybamboo board is used, different kinds of glue may be used, e.g. because of required moisture resistance. For the furniture board industry usually urea formaldehyde is used, but for example for 2-layer bamboo parquet, formaldehyde free glues are used while for veneer formaldehyde-, melamine-, and poly urethane glues are used [2], each with different eco-costs/kg.

Energy consumption/FU	**1.89 kWh/FU**

13. Sanding 1-layer board

According to [1], 400 m2 1-layer board can be processed per hour with the sanding machine (55-90 kW). Each FU consists of three layers, meaning that in the final board three 1-layer boards are required. This means 400/3 = 133.33 m2 of 3-layer board can be processed per hour. This corresponds to 133.33/2.98 (m2 per board) = 44.7 FU/hour, which corresponds to 1/44.7 = 0.022 hour/FU. Energy consumption per FU for the sanding machine is then 0.022 x 72.5 (average of 55-90 kW) = 1.62 kWh/FU.

Input in LCA: Sanding 1-layer board

Energy consumption/FU	**1.62 kWh/FU**

14. Glue application (3-layer board)

According to [1], gluing the boards together requires an additional 150-180 grams of glue per m2 (average: 165 g/m2). Since two planes need to be glued, 2 x 165 = 330 g/m2 is required, which corresponds to 330g x 2.98 m2 = 983 grams per FU (board) in wet conditions.

Input in LCA: Glue application (3-layer board)

Type of glue	**Urea formaldehyde complying with E1 norm**
Weight/amount of glue	**983 grams per FU (wet state)**

15. Pressing three layers to one board

After glue application to the 1-layer boards, the boards will be processed into 3-layer boards using multi layer cold presses (5.5kW). According to [1], around 80 m2 3-layer board can be processed per day (8 hours), corresponding to 10 m2/hour. This corresponds to 10/2.98 (m2 per board) = 3.35 FU/hour, which corresponds to 0.30 hour/FU. Energy consumption per FU for the press is then 5.5 x 0.3 = 1.65 kWh/FU.

Input in LCA: Pressing three layers to one board

Energy consumption/FU	**1.65 kWh/FU**

16. Sawing

In order to acquire boards of exact dimensions, the borders of the boards need to be sawn. According to [1] the sawing machine (5.5 kW) used can process 450 m2 of boards per day (8 hours), which corresponds to 450/8 = 56.25 m2/hour, which corresponds to 56.25/2.98 = 18.8 FUs/hour, which corresponds to 0.053 hour per FU. The energy consumption for sawing per FU is then 0.053 x 5.5 = 0.29 kWh/FU.

Input in LCA: Sawing

Energy consumption/FU	**0.29 kWh/FU**

17. Sanding 3-layer board

According to [1], 250 m2 3-layer board can be processed per hour with the sanding machine (55-90 kW), which corresponds to 250/2.98 (m2 per board) = 83.9 FU/hour, which corresponds to 1/83.9 = 0.012 hour/FU. Energy consumption per FU for the sanding machine is then 0.012 x 72.5 = 0.86 kWh

Input in LCA: Sanding 3-layer board

Energy consumption/FU	**0.86 kWh/FU**

18. Dust absorption (during all steps)
According to [1], there is a dust absorption system active in the board-producing factory (see box).
As explained in the box, the allocation of energy consumption per FU to the dust absorption system depends on the maximum number of FUs/hour that can be produced in the complete factory. The maximum output of the whole factory is determined by the critical process step (rough planing; see box). The maximum output of the rough planing activity (based on the use of three planers in the factory) is 2 x 3 = 6 FUs/hour, which means it takes 1/6 = 0.17 hour to produce one FU. The energy consumption per FU that can be allocated to dust absorption is then 0.17 x 51 kW (average of 22 - 80 kW) = 8.67 kWh/FU.

Box: Energy Production and Consumption by the Dust Absorption System (22-80 kW)

Since the dust absorption system applies to the complete factory, and is running all the time, it is very difficult to allocate its energy consumption to a specific machine or number of FUs produced. Since most machines are running at the same time, parallel processing strips and producing boards, at the end of the production chain there is a consistent output of boards. This output is dependent on the number of FUs (in the form of processed strips) that can be processed in every process step. The step that has the lowest FU/hour output determines the critical path (and thus energy consumption with respect to dust absorption) of the complete production system. To make things even more complex, many factories in China specialize in one specific production step (e.g. production rough strips, carbonization, etc.), so board producers usually outsource their critical production steps. With a production of 77 FUs every three days for bleached 3-layer board or even 77 FUs per ten days for carbonized 3-layer board (see later in this appendix), drying would be the critical production step. However, time consuming steps such as boiling, carbonizing and drying do not produce dust and are usually located in a different part of the factory [3]. The dust absorption system is used in the places where most dust is produced: near the planing-, sawing- and sanding machines. Of these machines, the rough planers usually have the lowest output (2 FUs/hour). To solve this problem usually more planers are used at the same time in many factories (3-4 planers; see photos of production step "rough planing" above). Still, since the presses and sanders have a higher capacity and are usually also available in multiple machines, the planers usually remain the critical factor.

Therefore, for this calculation it was assumed that the planers are the critical factor with an output of three planers of 3 x 2 = 6 FUs/hour. This means that if all machines run parallel to each other (which they do), then the planers determine the maximum output of FUs per hour for the factory as a whole. The consumption of the dust absorption system is therefore based on this figure.

Input in LCA: dust absorption system

Energy consumption/FU	**8.67 kWh/FU**

19. Transport from factory to harbor
After sanding, the boards are packed in containers ready for transport. For this assessment was calculated with a 20-foot container which has standard internal dimensions of 5.90 x 2.35 x 2.39 meters (33.2m3) and a maximum load of around 30 tons (including weight of the container of 2.3 tons), which was transported by a 28-ton truck, over a distance of 300 km (factory in Huangzhou to Shanghai harbor). For larger trucks and for sea transport the eco-costs are usually calculated based on the eco-costs per ton.km of a certain vehicle (empty return figures taken into account in the one-way distance). The amount of ton.km per FU is 41.7 kg x 300 km = 12.51 ton.km/FU. Based on the eco-costs/ton.km of a 28-ton truck the eco-costs per FU can then be calculated.

Input in LCA: Transport from factory to harbor

Distance	**300 km**
Kind of transport	**28-ton truck**
Ton km per FU	**12.51 ton.km/FU**

20. Transport from harbor to harbor
Calculations for the environmental burden for sea transport are based on transport with a trans-oceanic freight ship in a 20-foot container, with a travel distance from Shanghai to Rotterdam of 19208 kilometers. As found above, for sea transport the eco-costs are usually calculated based on the eco-costs per ton.km of the boat used (empty return figures taken into account in the one-way distance). The amount of ton.km per FU is 0.0417 tons x 19208 km = 801 ton.km/FU. Based on the eco-costs/ton.km of a 20-foot container transported by a trans-oceanic freight ship, the eco-costs per FU can then be calculated.

Input in LCA: Transport from harbor to harbor

Distance	**19208 km**
Kind of transport	**Trans-oceanic freight ship (20-foot container)**
Ton km per FU	**801 ton.km/FU**

21. Transport from harbor to warehouse (the Netherlands)
The distance from the harbor in Rotterdam to the warehouse in Zwaag is 115 km. For the calculation it was assumed that one 20ft container is transported by a 28-ton truck. The amount of ton.km per FU is 0.0417 tons x 115 km = 12.51 ton.km/FU. Based on the eco-costs/ton.km of a 28-ton truck the eco-costs per FU can then be calculated.

Input in LCA: Transport from harbor to warehouse (the Netherlands)

Distance	**115 km**
Kind of transport	**28-ton truck**
Ton km per FU	**4.80 ton.km/FU**

Results

All the input data of the various production- and transport activities found above, including the corresponding eco-costs, and the resulting overall eco-costs is summarized in table A1 below. The eco-costs were added by the second author, dr. Joost Vogtländer, based on the Eco-costs 2007 database available through the website www.ecocostsvalue.com (Vogtländer 2008).

Table A1: Input data and results for the environmental impact assessment of bleached 3-layer Plybamboo board

Process step	Amount	Unit	Eco-costs (€)/unit	Eco-costs (€)/FU	Eco-costs (€)/kg	%
1. Cultivation and harvesting from plantation Gasoline consumption	0.224	liter/FU	1.04/liter	0.233	0.0056	1.6%
2. Transport from plantation to strip manufacturing facility; Eco-costs of a 5-ton truck (transport of 23.1 FUs)	30	Km	0.243/km per 5t truck	0.316	0.0076	2.1%
3. Strip making: Energy consumption	1.38	kWh/ FU	0.109/kWh	0.150	0.0036	1.0%
4. Transport from strip manufacturing facility to factory; Eco-costs of a 10-ton truck (transport of 77.6 FUs).	600	Km	0.32/km per 10t truck	2.474	0.0593	16.8%
5. Rough planing: Energy consumption	8.62	kWh/ FU	0.109/kWh	0.940	0.0225	6.4%
6. Strip selection						
7. Bleaching: Energy consumption	1.59	kWh/ FU	0.109/kWh	0.173	0.0042	1.2%
7. Bleaching: Added amount of H_2O_2	5.62	Kg H_2O_2/FU	0.226/kg H_2O_2 50% solution	1.27	0.0305	8.6%
8. Drying: Energy consumption	10.4	kWh/FU	0.109/kWh	1.134	0.0272	7.7%
9. Fine planing: Energy consumption	5.8	kWh/FU	0.109/kWh	0.632	0.0152	4.3%
10. Strip selection						
11. Glue application (1-layer boards) Added amount of Urea formaldehyde (wet)	0.894	Kg /FU	0.57/kg	0.510	0.0122	3.5%
12. Pressing strips to 1-layer board: Energy	1.89	kWh/FU	0.109/kWh	0.206	0.0049	1.4%
13. Sanding 1-layer board: Energy	1.62	kWh/FU	0.109/kWh	0.177	0.0042	1.2%
14. Glue application (3-layer board) Added amount of Urea formaldehyde (wet)	0.983	kg/FU	0.57/kg	0.56	0.0134	3.8%
15. Pressing three layers to one board: Energy	1.65	kWh/FU	0.109/kWh	0.18	0.0043	1.2%
16. Sawing: Energy consumption	0.29	kWh/FU	0.109/kWh	0.032	0.0008	0.2%
17. Sanding 3-layer board: Energy	0.86	kWh/FU	0.109/kWh	0.094	0.0022	0.6%
18. Dust absorption (during all steps) Energy consumption	8.67	kWh/FU	0.109/kWh	0.945	0.0227	6.4%
19. Transport from factory to harbor Eco-costs (28-ton truck)	12.51	ton.km/FU	0.033/ton.km	0.413	0.0099	2.8%
20. Transport from harbor to harbor Eco-costs (20ft container in a trans-oceanic freight ship)	801	ton.km/FU	0.0052/ton.km	4.165	0.0999	28.2%
21. Transport from harbor to warehouse Eco-costs (28-ton truck)	4.80	ton.km/FU	0.033/ton.km	0.158	0.0038	1.1%
Total eco-costs (€)				**14.76**	**0.354**	**100.0%**

Carbonized Plybamboo Board (3-layer)

The input data as described above for the bleached 3-layer board applies in total to the carbonized version except for activity 7 (preservation & coloring) and activity 8 (drying), which are adjusted below.

7. Preservation & coloring: carbonization



Instead of bleaching, the bamboo strips alternatively can be carbonized for preservation and coloring. This is done by melting the sugars in the bamboo strips under high pressure (0.21-0.25 mPa) and temperature (120-130 degrees Celsius) with the use of steam [1]. As a result of the carbonization process the bamboo strip will be preserved and acquires a darker, caramelized color.

According to [1], the bamboo strips will go through two rounds of carbonization, which take 150-170 minutes for each round (depending on the level of darkness required for the board). In the first round 4000 strips can be processed per day (8 hours), and in the second round 6000 strips per day.
For the first round 4000/8 strips = 500 strips can be processed per hour, corresponding to 500/260 = 1.92 FU/hour, which corresponds to 1/1.92 = 0.52 hour per FU.
For the energy consumption of the carbonization kettle for the first carbonization round this implies the following. According to [1], the carbonization kettle is powered by a carbonizing boiler (1.5kW) as well as the 2-ton boiler (3.94 kW allocated to one carbonization kettle; see box "energy consumption by the 2-ton boiler" above). The energy consumption per FU is then: (1.5 + 3.94) x 0.52 = 2.83 kWh/FU.
For the second carbonization round, the same calculation can be made, but for 6000 strips instead of 4000 strips. The energy consumption per FU is then: (1.5 + 3.94) x 0.35 = 1.9 kWh/FU.
Total energy consumption during carbonization is then 2.83 + 1.9 = 4.73 kWh/FU.

Input in LCA: Carbonization

Energy consumption/FU	**4.73 kWh/FU**

8. Drying
After carbonizing, the strips are dried in a drying chamber. Besides the energy consumption of the drying chamber itself (15kW), steam is used in the drying chamber derived from the boiler (1.64 kW, see box before). According to [1], the drying room is able to dry 30000 strips at once. The drying times for carbonized strips are different from those for bleached strips. Carbonized strips require a 168-hour drying cycle after the first carbonization round and a 72-hour drying cycle after the second carbonization round (in total 240 hours). This means that 30.000/260 = 115.4 FUs can be dried in 240 hours,

corresponding to 115.4/240 = 0.48 FU/hour, which corresponds to 1/0.48 = 2.08 hour per FU. Energy consumption per FU is then 15 + 1.64 = 16.64 Kwh x 2.08 = 34.6 kWh/FU.

Input in LCA: Drying carbonized strips

Energy consumption/FU	**34.6 kWh/FU**

Results

All the input data of the various production- and transport activities found above, including the corresponding eco-costs and the resulting overall eco-costs for the production of one carbonized 3-layer Plybamboo board is summarized in table A2 below. The eco-costs were added by the second author, dr. Joost Vogtländer, based on the Eco-costs 2007 database available through the website www.ecocostsvalue.com (Vogtländer 2008).

Table A2: Input data and results for the environmental impact assessment of carbonized 3-layer Plybamboo board

Process step	Amount	Unit	Eco-costs (€)/unit	Eco-costs (€)/FU	Eco-costs (€)/kg	%
1. Cultivation and harvesting from plantation Gasoline consumption	0.224	liter/FU	1.04/liter	0.233	0.0056	1.4%
2. Transport from plantation to strip manufacturing facility; Eco-costs of a 5-ton truck (transport of 23.1 FUs)	30	Km	0.243/km per 5t truck	0.316	0.0076	1.9%
3. Strip making: Energy consumption	1.38	kWh/ FU	0.109/kWh	0.150	0.0036	0.9%
4. Transport from strip manufacturing facility to factory; Eco-costs of a 10-ton truck (transport of 77.6 FUs).	600	Km	0.32/km per 10t truck	2.474	0.0593	15.0%
5. Rough planing: Energy consumption	8.62	kWh/ FU	0.109/kWh	0.940	0.0225	5.7%
6. Strip selection						
7. Carbonization: Energy consumption	4.73	kWh/FU	0.109/kWh	0.516	0.0124	3.1%
8. Drying: Energy consumption	34.6	kWh/FU	0.109/kWh	3.771	0.09	22.9%
9. Fine planing: Energy consumption	5.8	kWh/FU	0.109/kWh	0.632	0.0152	3.8%
10. Strip selection						
11. Glue application (1-layer boards) Added amount of Urea formaldehyde (wet)	0.894	Kg /FU	0.57/kg	0.510	0.0122	3.1%
12. Pressing strips to 1-layer board: Energy	1.89	kWh/FU	0.109/kWh	0.206	0.0049	1.3%
13. Sanding 1-layer board: Energy	1.62	kWh/FU	0.109/kWh	0.177	0.0042	1.1%
14. Glue application (3-layer board) Added amount of Urea formaldehyde (wet)	0.983	kg/FU	0.57/kg	0.56	0.0134	3.4%
15. Pressing three layers to one board: Energy	1.65	kWh/FU	0.109/kWh	0.18	0.0043	1.1%
16. Sawing: Energy consumption	0.29	kWh/FU	0.109/kWh	0.032	0.0008	0.2%
17. Sanding 3-layer board: Energy	0.86	kWh/FU	0.109/kWh	0.094	0.0022	0.6%
18. Dust absorption (during all steps) Energy consumption	8.67	kWh/FU	0.109/kWh	0.945	0.0227	5.7%
19. Transport from factory to harbor Eco-costs (28-ton truck)	12.51	ton.km/FU	0.033/ton.km	0.413	0.0099	2.5%
20. Transport from harbor to harbor Eco-costs (20ft container in a trans-oceanic freight ship)	801	ton.km/FU	0.0052/ton.km	4.165	0.0999	25.3%
21. Transport from harbor to warehouse Eco-costs (28-ton truck)	4.80	ton.km/FU	0.033/ton.km	0.158	0.0038	1.0%
Total eco-costs (€)				**16.47**	**0.395**	**100.0%**

Plybamboo Board (1-layer)

A similar calculation was made for 1-layer Plybamboo board in various variations (carbonized or bleached, plain pressed or side pressed). The FU used as a base element for this assessment is one board of 2440 x 1220 x 5 mm (2.98 m2), with a weight of 10.4 kilograms (based on a density of 700 kg/m3), in which 61 fine planed strips (2500 x 20 x 5 mm) are used. For the side pressed version it is assumed that each of these strips is cut up into four smaller pieces of 2440 x 5 x 5 mm after fine planing.

The input data and results for the various production- and transport activities, including the corresponding eco-costs and the resulting overall eco-costs, for the production of the various 1-layer Plybamboo boards are summarized in the tables below. The eco-costs were added by the second author, dr. Joost Vogtländer, based on the Eco-costs 2007 database available through the website www.ecocostsvalue.com (Vogtländer 2008).

Table A3: Input data and results for the environmental impact assessment of 1-layer plain pressed Plybamboo board (bleached)

Process step	Amount	Unit	Eco-costs (€)/unit	Eco-costs (€)/FU	Eco-costs (€)/kg	%
1. Cultivation and harvesting from plantation Gasoline consumption	0.06	liter/FU	1.04/liter	0.058	0.0056	1.7%
2. Transport from plantation to strip manufacturing facility; Eco-costs of a 5-ton truck (transport of 92.4 FUs)	30	Km	0.243/km per 5t truck	0.079	0.0075	2.3%
3. Strip making: Energy consumption	0.35	kWh/ FU	0.109/kWh	0.0376	0.0036	1.1%
4. Transport from strip manufacturing facility to factory; Eco-costs of a 10-ton truck (transport of 310.4 FUs).	600	Km	0.32/km per 10t truck	0.619	0.0590	17.7%
5. Rough planing: Energy consumption	2.16	kWh/ FU	0.109/kWh	0.235	0.0224	6.7%
6. Strip selection						
7. Bleaching: Energy consumption	0.40	kWh/ FU	0.109/kWh	0.043	0.0041	1.2%
7. Bleaching: Added amount of H_2O_2	1.41	kg H_2O_2/FU	0.226/kg H_2O_2 50% solution	0.318	0.030	9.1%
8. Drying: Energy consumption	2.60	kWh/FU	0.109/kWh	0.283	0.027	8.1%
9. Fine planing: Energy consumption	1.45	kWh/FU	0.109/kWh	0.158	0.015	4.5%
10. Strip selection						
11. Glue application (1-layer boards) Added amount of Urea formaldehyde (wet)	0.149	kg/FU	0.57/kg	0.0849	0.0081	2.4%
12. Pressing strips to 1-layer board: Energy	0.64	kWh/FU	0.109/kWh	0.0698	0.0067	2.0%
13. Sawing: Energy consumption	0.29	kWh/FU	0.109/kWh	0.0316	0.0030	0.9%
14. Sanding 1-layer board: Energy	0.54	kWh/FU	0.109/kWh	0.0589	0.0056	1.7%
15. Dust absorption (during all steps) Energy consumption	2.17	kWh/FU	0.109/kWh	0.236	0.023	6.8%
16. Transport from factory to harbor Eco-costs (28-ton truck)	3.13	ton.km/FU	0.033/ton.km	0.1032	0.0098	3.0%
17. Transport from harbor to harbor Eco-costs (20ft container in a trans-oceanic freight ship)	200.24	ton.km/FU	0.0052/ton.km	1.0413	0.0993	29.8%
18. Transport from harbor to warehouse Eco-costs (28-ton truck)	1.20	ton.km/FU	0.033/ton.km	0.0396	0.0038	1.1%
Total eco-costs (€)				**3.50**	**0.333**	**100.0%**

Table A4: Input data and results for the environmental impact assessment of 1-layer side pressed Plybamboo board (bleached)

Process step	Amount	Unit	Eco-costs (€)/unit	Eco-costs (€)/FU	Eco-costs (€)/kg	%
1. Cultivation and harvesting from plantation Gasoline consumption	0.06	liter/FU	1.04/liter	0.058	0.0056	1.6%
2. Transport from plantation to strip manufacturing facility; Eco-costs of a 5-ton truck (transport of 92.4 FUs)	30	Km	0.243/km per 5t truck	0.079	0.0075	2.1%
3. Strip making: Energy consumption	0.35	kWh/ FU	0.109/kWh	0.0376	0.0036	1.0%
4. Transport from strip manufacturing facility to factory; Eco-costs of a 10-ton truck (transport of 310.4 FUs).	600	Km	0.32/km per 10t truck	0.619	0.0590	16.5%
5. Rough planing: Energy consumption	2.16	kWh/ FU	0.109/kWh	0.235	0.0224	6.3%
6. Strip selection						
7. Bleaching: Energy consumption	0.40	kWh/ FU	0.109/kWh	0.043	0.0041	1.2%
7. Bleaching: Added amount of H_2O_2	1.41	kg H_2O_2/FU	0.226/kg H_2O_2 50% solution	0.318	0.030	8.5%
8. Drying: Energy consumption	2.60	kWh/FU	0.109/kWh	0.283	0.027	7.6%
9. Fine planing: Energy consumption	1.45	kWh/FU	0.109/kWh	0.158	0.015	4.2%
10. Strip selection						
11. Glue application (1-layer boards) Added amount of Urea formaldehyde (wet)	0.596	kg/FU	0.57/kg	0.34	0.0324	9.1%
12. Pressing strips to 1-layer board: Energy	0.64	kWh/FU	0.109/kWh	0.0698	0.0067	1.9%
13. Sawing: Energy consumption	0.29	kWh/FU	0.109/kWh	0.0316	0.0030	0.8%
14. Sanding 1-layer board: Energy	0.54	kWh/FU	0.109/kWh	0.0589	0.0056	1.6%
15. Dust absorption (during all steps) Energy consumption	2.17	kWh/FU	0.109/kWh	0.236	0.023	6.3%
16. Transport from factory to harbor Eco-costs (28-ton truck)	3.13	ton.km/FU	0.033/ton.km	0.1032	0.0098	2.8%
17. Transport from harbor to harbor Eco-costs (20ft container in a trans-oceanic freight ship)	200.24	ton.km/FU	0.0052/ton.km	1.0413	0.0993	27.8%
18. Transport from harbor to warehouse Eco-costs (28-ton truck)	1.20	ton.km/FU	0.033/ton.km	0.0396	0.0038	1.1%
Total eco-costs (€)				**3.75**	**0.358**	**100.0%**

Table A5: Input data and results for the environmental impact assessment of 1-layer plain pressed Plybamboo board (carbonized)

Process step	Amount	Unit	Eco-costs (€)/unit	Eco-costs (€)/FU	Eco-costs (€)/kg	%
1. Cultivation and harvesting from plantation Gasoline consumption	0.06	liter/FU	1.04/liter	0.058	0.0056	1.5%
2. Transport from plantation to strip manufacturing facility; Eco-costs of a 5-ton truck (transport of 92.4 FUs)	30	Km	0.243/km per 5t truck	0.079	0.0075	2.0%
3. Strip making: Energy consumption	0.35	kWh/ FU	0.109/kWh	0.0376	0.0036	1.0%
4. Transport from strip manufacturing facility to factory; Eco-costs of a 10-ton truck (transport of 310.4 FUs).	600	Km	0.32/km per 10t truck	0.619	0.0590	15.8%
5. Rough planing: Energy consumption	2.16	kWh/ FU	0.109/kWh	0.235	0.0224	6.0%
6. Strip selection						
7. Carbonization: Energy consumption	1.18	kWh/ FU	0.109/kWh	0.129	0.0123	3.3%
8. Drying: Energy consumption	8.65	kWh/FU	0.109/kWh	0.943	0.090	24.0%
9. Fine planing: Energy consumption	1.45	kWh/FU	0.109/kWh	0.158	0.015	4.0%
10. Strip selection						
11. Glue application (1-layer boards)	0.149	kg/FU	0.57/kg	0.085	0.0081	2.2%

Added amount of Urea formaldehyde (wet)						
12. Pressing strips to 1-layer board: Energy	0.64	kWh/FU	0.109/kWh	0.0698	0.0067	1.8%
13. Sawing: Energy consumption	0.29	kWh/FU	0.109/kWh	0.0316	0.0030	0.8%
14. Sanding 1-layer board: Energy	0.54	kWh/FU	0.109/kWh	0.0589	0.0056	1.5%
15. Dust absorption (during all steps) Energy consumption	2.17	kWh/FU	0.109/kWh	0.236	0.023	6.0%
16. Transport from factory to harbor Eco-costs (28-ton truck)	3.13	ton.km/FU	0.033/ton.km	0.1032	0.0098	2.6%
17. Transport from harbor to harbor Eco-costs (20ft container in a trans-oceanic freight ship)	200.24	ton.km/FU	0.0052/ton.km	1.0413	0.0993	26.5%
18. Transport from harbor to warehouse Eco-costs (28-ton truck)	1.20	ton.km/FU	0.033/ton.km	0.0396	0.0038	1.0%
Total eco-costs (€)				**3.92**	**0.374**	**100.0%**

Table A6: Input data and results for the environmental impact assessment of 1-layer side pressed Plybamboo board (carbonized)

Process step	Amount	Unit	Eco-costs (€)/unit	Eco-costs (€)/FU	Eco-costs (€)/kg	%
1. Cultivation and harvesting from plantation Gasoline consumption	0.06	liter/FU	1.04/liter	0.058	0.0056	1.4%
2. Transport from plantation to strip manufacturing facility; Eco-costs of a 5-ton truck (transport of 92.4 FUs)	30	Km	0.243/km per 5t truck	0.079	0.0075	1.9%
3. Strip making: Energy consumption	0.35	kWh/ FU	0.109/kWh	0.0376	0.0036	0.9%
4. Transport from strip manufacturing facility to factory; Eco-costs of a 10-ton truck (transport of 310.4 FUs).	600	Km	0.32/km per 10t truck	0.619	0.0590	14.8%
5. Rough planing: Energy consumption	2.16	kWh/ FU	0.109/kWh	0.235	0.0224	5.6%
6. Strip selection						
7. Carbonization: Energy consumption	1.18	kWh/ FU	0.109/kWh	0.129	0.0123	3.1%
8. Drying: Energy consumption	8.65	kWh/FU	0.109/kWh	0.943	0.090	22.6%
9. Fine planing: Energy consumption	1.45	kWh/FU	0.109/kWh	0.158	0.015	3.8%
10. Strip selection						
11. Glue application (1-layer boards) Added amount of Urea formaldehyde (wet)	0.596	kg/FU	0.57/kg	0.34	0.0324	8.1%
12. Pressing strips to 1-layer board: Energy	0.64	kWh/FU	0.109/kWh	0.0698	0.0067	1.7%
13. Sawing: Energy consumption	0.29	kWh/FU	0.109/kWh	0.0316	0.0030	0.8%
14. Sanding 1-layer board: Energy	0.54	kWh/FU	0.109/kWh	0.0589	0.0056	1.4%
15. Dust absorption (during all steps) Energy consumption	2.17	kWh/FU	0.109/kWh	0.236	0.023	5.7%
16. Transport from factory to harbor Eco-costs (28-ton truck)	3.13	ton.km/FU	0.033/ton.km	0.1032	0.0098	2.5%
17. Transport from harbor to harbor Eco-costs (20ft container in a trans-oceanic freight ship)	200.24	ton.km/FU	0.0052/ton.km	1.0413	0.0993	24.9%
18. Transport from harbor to warehouse Eco-costs (28-ton truck)	1.20	ton.km/FU	0.033/ton.km	0.0396	0.0038	0.9%
Total eco-costs (€)				**4.18**	**0.398**	**100.0%**

Plybamboo Veneer

A relatively new bamboo product from China is bamboo veneer with a thickness of 0.6 mm. This product is available in the same pattern (side pressed and plain pressed) and colors (carbonized and bleached) as other Plybamboo materials. The production process of the veneer is very similar to that of the 1-layer Plybamboo board, based on which an estimation can be made for the eco-costs/kg for the production of veneer. For the production of veneer an extra process step is added in which the veneer is sliced, like a slice of cheese, from a large laminated bamboo block (in essence consisting of many 1-layer boards) with a machine, specially developed for this purpose. Since the veneer is very thin, it is more susceptible to deficiencies, which results in a higher material loss after quality control than for the 1-layer boards. After slicing the veneer from the block, only 40-45% of plain pressed bamboo veneer meets the highest quality requirements and 55-60% is discarded, while for side pressed bamboo veneer 70-75% meets the highest quality requirements and 25-30% is discarded [2]. This means that compared to the production of 1-layered boards for plain pressed bamboo veneer 100%/42.5% = 2.35 times more material is needed. For side pressed bamboo 100%/72.5% = 1.38 times more material is needed compared to the 1-layered boards. Based on these ratios the eco-costs/kg, found for 1-layer Plybamboo board (see above), can be modified to provide the eco-costs for the various types of bamboo veneer (see table below).

Table A7: Eco-costs per kilogram of Plybamboo veneer in several variations

Product	Eco-costs (€)/kg
Plain pressed veneer (bleached)	0.78
Side pressed veneer (bleached)	0.49
Plain pressed veneer (carbonized)	0.88
Side pressed veneer (carbonized)	0.55

Stem

General Data

The FU used as a base element for this assessment is one 5.33 meter-long Moso stem (diameter: 10 cm at bottom, 7 cm at top), which weighs 7.65 kg in its dry state (see table 3.3 in section 3.2 for the establishment of the weight). If the stem is not used as input for board production (see step 1 in the production process of the various bamboo boards above), it will have to be preserved and dried separately; see production process below.

Full Production Process (Cradle to Site)

1. Cultivation and harvesting bamboo from sustainably managed plantations
2. Transport to stem preservation facility
3. Preservation and drying
4. Transport from stem preservation facility to harbor
5. Transport from harbor to harbor
6. Transport from harbor to warehouse

Determination of Input Data per Process Step

1. Cultivation and harvesting bamboo from sustainably managed plantations

In the calculation it is assumed that no fertilizers and pesticides were used on the plantations from which the stems were extracted. Harvesting figures are based on [5], in which is estimated that 234 stems can be harvested with chainsaws on one gallon (3.785 liters) of gasoline, which comes down to 0.016 liters of gasoline per stem.

Input in LCA: Cultivation and harvesting of bamboo from sustainably managed plantations

Gasoline consumption	**0.016 liters/FU**

2. Transport to stem preservation facility

According to [1] an average of around 320 stems (FUs) with a length of 8 meters are transported per truck load with a 5-ton truck over a distance of 15 kilometers [2]. For small trucks the eco-costs are calculated based on the eco-costs per km of a certain vehicle, based on an empty truck load for the return (thus calculating with 2 x 15 = 30 km).

Input in LCA: Transport to stem preservation facility

Distance	**15 km**
Kind of transport	**5-ton truck**
Amount of FU per load	**320 stems (FUs)**

3. Preservation and drying

According to [5], preservation of stems is best executed through the Boucherie method powered by an air pump, through which the sap of the stem is completely replaced by a boron solution. Boron is perceived as an environmentally friendly preservative, which is also commonly used as a fertilizer. The air pump consumes 1 kWh per stem [5]. After preservation the stems are usually dried in the open air.

Input in LCA: Transport to stem preservation facility

Energy consumption per FU	**1 kWh/stem (FU)**

4. Transport from stem preservation facility to harbor

After drying the stems are packed in containers ready for transport. Since bamboo stems are relatively light, for this assessment it was calculated with a 40-foot container which has standard internal dimensions of 12.0 x 2.35 x 2.39 meters (67.7m3) and a maximum load of around 32 tons (including weight of the container of 3.7 tons). In a 40-foot container around 1000 stems of 5.33 meters (FU) long and a diameter of maximum 10 cm can be transported per truckload. The stems are then transported with a 28-ton truck over a distance of 600 km to the harbor of Shang Hai [1, 2]. For larger trucks the eco-costs are usually calculated based on the eco-costs per ton km of a certain vehicle (empty return figures taken into account in the one-way distance). The amount of ton.km per FU is 0.00765 tons x 600 km = 4.59 ton.km/FU. Based on the eco-costs/ton.km of a 28-ton truck the eco-costs per FU can then be calculated.

Input in LCA: Transport from stem preservation facility to harbor

Distance	**600 km**
Kind of transport	**28-ton truck**
Ton km per FU	**4.59 ton.km/FU**

5. Transport from harbor to harbor

The calculation to determine the environmental burden for sea transport was based on transport with a trans-oceanic freight ship in a 40-foot container, with a travel distance Shanghai-Rotterdam of 19208 kilometers. While the environmental burden of sea transport is usually based on the weight of the load (ton.km; see the summary tables for the various Plybamboo boards above), for loads under 400 kg/m3 it should be calculated with a volume bound eco-cost indicator (m3.km; see Vogtländer 2008). Therefore, the eco-costs were calculated based on the eco-costs per m3.km of the boat used (empty return figures taken into account in the one-way distance). One FU takes up 67.7 m3/1000 FU = 0.068 m3 of the container. The amount of m3.km per FU is then 0.068 m3 x 19208 km = 1300 m3.km/FU. Based on the eco-costs/m3.km of a 40-foot container transported by a trans-oceanic freight ship, the eco-costs per FU can then be calculated.

Input in LCA: Transport from harbor to harbor

Distance	**19208 km**
Kind of transport	**trans-oceanic freight ship (40-foot container)**
m3.km per FU	**1300 m3.km/FU**

6. Transport from harbor to warehouse (the Netherlands)

The distance from the Rotterdam harbor to the Zwaag warehouse is 115 km. For the rest of the calculation the same parameters as for step 4 are used.

Input in LCA: Transport from harbor to warehouse (the Netherlands)

Distance	**115 km**
Kind of transport	**28-ton truck**
Ton km per FU	**0.88 ton.km/FU**

Results

All the input data of the various production- and transport activities found above, including the corresponding eco-costs and the resulting overall eco-costs is summarized in table A8 below.

Table A8: Input data and results for the environmental impact assessment of a 5.3-meter long bamboo stem

Process step	Amount	Unit	Eco-costs (€)/unit	Eco-costs (€)/FU	Eco-costs (€)/kg	%
1. Cultivation and harvesting from plantation Gasoline consumption	0.016	liter/FU	1.04/liter	0.017	0.0022	0.3%
2. Transport from to stem processing facility; Eco-costs of a 5-ton truck (transport 320 FUs)	30	Km	0.243/km per 5t truck	0.0228	0.0030	0.4%
3. Preservation & drying: Energy consumption	1	kWh/ FU	0.109/kWh	0.109	0.0142	1.7%
4. Transport from stem preservation facility to harbor (28-ton truck)	4.59	ton.km/FU	0.033/ton.km	0.151	0.0226	2.7%
5. Transport from harbor to harbor Eco-costs (volume based; 400ft container in a trans-oceanic freight ship)	1300	m3.km/FU	0.0041/m3.km	5.330	0.795	94.5%
6. Transport from harbor to warehouse Eco-costs (28-ton truck)	0.88	ton.km/FU	0.033/ton.km	0.029	0.0043	0.5%
Total eco-costs (€)				**5.66**	**0.842**	**100.0%**

Strand Woven Bamboo

Because of the rather different production process, the production of Strand Woven Bamboo (SWB) is explained below in a more elaborate manner.

General Data

Strand Woven Bamboo (SWB) is a relatively new industrial bamboo material that can be used indoors and outdoors. This calculation is based on the carbonized version of the outdoor product (with a higher glue content and higher compression level than the indoor version). SWB floor pieces and planks are sawn from a beam (1900 x 110 x 140 mm) made from compressed rough bamboo strips and resin [3]. Due to the compression and the high resin content the density of SWB is high (1080 kg/m3). Taking sawing and sanding losses into account, per beam 8 planks of 1900 x 100 x 15 mm can be made, which is chosen as the FU for the calculation. The beam weighs 0.029 m3 x 1080 = 31.6 kg, while the plank weighs 0.00285 m3 x 1080 = 3.08 kg.
Since the input strips for SWB will be compressed they do not have to be uniform in size and shape, which means no stringent quality control is needed for the input strips for SWB (in contrast with Plybamboo boards). According to [3], based on visits to various SWB producers, the size of the input strips may vary in width (1-3 cm) and in thickness (1.5-3.5 mm). To keep this calculation workable was calculated with an average input strip size of 2000 x 20 x 3mm (0.000114 m3), with a weight of 0.080 kg (= 80 grams).

In order to calculate the number of strips used per beam, first the amount of resin used needs to be taken into account. According to [4], Phenol Formaldehyde is used as glue, of which the solid content in the final product is 23%. The weight of Phenol Formaldehyde lies around 1200 kg/m3 both in wet and in dry states. For the calculation, it is assumed that the weight of the resin is more or less the same as the weight of the compressed bamboo. This means that in the beam the amount of resin is 23% x 31.6 kg = 7.27 kg. The rest of the weight is made up by compressed bamboo material: 31.6 -7.27 = 24.3 kg. The volume of the bamboo material in the beam is 77% x 0.029 m3 = 0.022 m3. Since the material is compressed, an amount of 1080/700 =1.54 times more raw bamboo material is needed to produce the beam, which corresponds to an amount of 1.54 x 0.022 = 0.034 m3 of bamboo material (strips). This corresponds to a number of 0.034/0.000114 = 302 strips per beam, and 298/8 = 38 strips per plank (FU).

Full Production Process

1. Cultivation and harvesting of bamboo on sustainably managed plantations
2. Transport from plantation to strip manufacturing facility
3. Strip making
4. Transport from strip manufacturing facility to factory
5. Rough planing
6. Splitting strips in half
7. Preservation & coloring: carbonizing
8. Drying
9. Crushing strips
10. Glue application
11. Pressing strips to beam
12. Activating glue in oven
13. Sawing beams
14. Sawing planks
15. Sanding planks
16. Transport from factory to harbor
17. Transport from harbor to harbor
18. Transport from harbor to warehouse

Determination of Input Data per Process Step

1. Cultivation and harvesting of bamboo on sustainably managed plantations

In the calculation it is assumed that no fertilizers and pesticides were used on the plantations from which the stems were extracted. Harvesting figures are based on [5], in which is estimated that 234 stems can be harvested with chainsaws on one gallon (3.785 liters) of gasoline, which comes down to 0.016 liters of gasoline per stem.

Since the input strips for SWB have a different size (2000 x 20 x 3mm) than the input strips for Plybamboo, the stem will be cut in four pieces, 2 m long, in the strip manufacturing facility. If we refer to the measures in table 3.3 in section 3.2 the number of strips that can be sourced from the four 2 m segments deriving from an 8 meter long stem can be estimated, taking into account the tapering character of the stem:

- 0-2 meter: 2 x 12 = 24 strips (2000 x 20 x 3)
- 2-4 meter: 2 x 10 = 20 strips
- 4-6 meter: 1 x 8 = 8 strips
- 6-8 meter: 1 x 6 = 6 strips

In total 58 strips can be sourced per stem. One FU consists of 38 strips. This means that per FU 38/58 = 0.65 stems are necessary. This means that per FU: 0.61 x 0.016 = 0.0104 liters of gasoline are consumed.

Input in LCA: Cultivation and harvesting of bamboo on sustainably managed plantation

Gasoline consumption	**0.0104 liters/FU**

2. Transport from plantation to strip manufacturing facility

According to [1], an average of around 320 stems with a length of 8 meters are transported per truck load with a 5-ton truck over a distance of 15 kilometers [2], which results in 320 stems/0.61 stems per FU (see step 1) = 492.3 FUs (planks) being transported per truck load. For small trucks the eco-costs are usually calculated based on the eco-costs per km of a certain vehicle, based on an empty truckload for the return (thus calculating with 2 x 15 = 30 km).

Input in LCA: Transport plantation to strip manufacturing facility

Distance	**30 km**
Kind of transport	**5-ton truck**
Amount of FU per load	**492.3 FUs**

3. Strip making

According to [1], 9000 strips (full wall thickness) can be produced in 8 hours with the strip making machine (5.5 kW), which corresponds to 1125 strips per hour. From 76% (44/58) of the strips produced in this step, two 3 mm thick strips can be made (in step 6), which corresponds to (1125 x 1.76 strips)/38 = 52 FUs (planks)/hour. It takes 1/ 52 = 0.019 hour to produce one FU. Energy consumption per FU is then 0.019 hour x 5.5 kW = 0.10 kWh/FU.

Input in LCA: Strip making

Energy consumption/FU	**0.10 kWh/FU**

4. Transport from strip manufacturing facility to factory

According to [1, 2], 8 tons of strips are transported per truck load (10-ton truck) from the strip processing facility to the factory, over 300 kilometers. One rough strip measures approximately: 2.0 x 0.023 x 0.009 m = 0.00041m3 x 700 kg/m3 = 0.29 kg per strip.

8000 kg per load means: 8000/0.29 = 27586 strips of 2.0 m long are transported per truckload. As found above, from 76% of the full wall thickness strips, two 3 mm thick strips can be made (in step 6), which corresponds to (27586 x 1.76 strips)/38 strips per FU = 1277.7 FUs, which are transported per truckload. For small trucks the eco-costs are usually calculated based on the eco-costs per km of a certain vehicle, based on an empty truckload for the return (thus calculating with 2 x 300 = 600 km).

Input in LCA: Transport from strip manufacturing facility to factory

Distance	**600 km**
Kind of transport	**10-ton truck**
Amount of FU per load	**1277.7 planks (FU)**

5. Rough planing
According to [1], 4500 strips can be produced in 8 hours with the rough planer (15-20 kW), which corresponds to 562 strips per hour, which corresponds to 562 × 1.76 strips (see explanation in previous steps)/38 strips per FU = 26.0 FUs (planks) per hour. It takes 1/26.0 = 0.038 hour to produce one FU. Energy consumption per FU is then 0.038 hour × 17.5 kW = 0.66 kWh/FU.

Input in LCA: Rough Planing

Energy consumption/FU	**0.66 kWh/FU**

6. Splitting strips in half
After rough planning, the thicker rough strips (thickness 6 mm) will be divided by a splitter into two smaller strips, with a thickness of 3 mm. According to [3], the cutting machine has more or less a similar processing speed as the fine planers (see Plybamboo calculation) in which 38-40 meters of strips can be processed per minute, which corresponds to 20 2-m long strips/minute, which corresponds to 60 × 20 × 1.76 = 2112 strips per hour, which corresponds to 2112 strips/38 strips per FU = 55.6 FUs (planks) per hour.
It is assumed that the power of the strip splitter is the same as for the strip making machine in step 3 (5.5 kW). It takes 1/55.6 = 0.018 hour to produce one FU. Energy consumption per FU is then 0.018 hour × 5.5 kW = 0.10 kWh/FU.

Input in LCA: Splitting strips in half

Energy consumption/FU	**0.10 kWh/FU**

7. Preservation & coloring: Carbonization
Figures for carbonization can largely be based on the figures for carbonizing strips for Plybamboo production with the difference that the strips used here are half the size of the strips used for Plybamboo production, which means twice the number of strips can be processed in the same time.
According to [1], the bamboo strips will go through two rounds of carbonization, which takes 150-170 minutes for each round (depending on the level of darkness required). In the first round 8000 strips can be processed per day (8 hours), and in the second round 12000 strips can be processed per day.
For the first round 8000 strips can be processed in 8 hours, which means 1000 strips per hour, corresponding to 1000/38 = 26.3 FUs/hour, which corresponds to 1/26.3 = 0.038 hour per FU.
For the energy consumption of the carbonization kettle for the first carbonization round this implies the following. According to [1], the carbonization kettle is powered by a carbonizing boiler (1.5kW) as well as the 2-ton boiler (3.94 kW allocated to one carbonization kettle, see box above). The energy consumption per FU is then: (1.5 + 3.94) × 0.038 = 0.21 kWh/FU. For the second carbonization round the same calculation can be made, but for 12000 strips instead of 8000 strips. The energy consumption per FU is then: (1.5 + 3.94) × 0.025 = 0.14 kWh/FU. Total energy consumption during carbonization is then 0.21 + 0.14 = 0.35 kWh/FU

Input in LCA: Carbonization

Energy consumption/FU	**0.35 kWh/FU**

8. Drying
The figures below can largely be based on the figures for drying carbonized strips for board production with the difference that the strips used here are half the size of the strips used for Plybamboo production, which means twice the number of strips can be processed in the same time.
After carbonization the strips will be dried in a drying chamber. Besides the energy consumption of the drying chamber itself (15 kW), there is steam used in the drying chamber deriving from the 2-ton boiler (1.64 kW; see box before). According to [1], the drying room has a capacity to dry 60000 strips at once. Carbonized strips require a 168 h (7 days) drying cycle after the first carbonization round and a 72 h drying cycle after the second round (in total 240 hours).
This means that 60.000/38 = 1578.9 FUs can be dried in 240 hours, corresponding to 1578.9/240 = 6.58 FU/hour, which corresponds to 1/6.58 = 0.15 hour per FU. Energy consumption per FU is then 15 + 1.64 = 16.64 Kwh × 0.15 = 2.58 kWh/FU.

Input in LCA: Drying

Energy consumption/FU	**2.58 kWh/FU**

9. Crushing strips

To achieve a better glue adhesion and facilitate the pressing procedure later, the strips are crushed by a simple machine (see photo on the right). The crushing machine has more or less a similar processing speed as the planers [3], in which 38-40 meters of strips can be processed per minute, which corresponds to 20 strips/minute, which corresponds to 1200 strips per hour, which corresponds to 1200 strips/38 strips per FU = 31.5 FUs (planks)/hour.
It is assumed that the power of the crusher is the same as the splitter in step 3 (5.5 kW). It takes 1/31.5 = 0.032 hour to produce one FU. Energy consumption per FU is then 0.032 hour x 5.5 kW = 0.17 kWh/FU

Input in LCA: Crushing strips

Energy consumption/FU	**0.17 kWh/FU**

10. Glue application
As a next step the crushed strips will be soaked in Phenol formaldehyde resin. As was already mentioned in the introduction of the SWB calculation, the amount of resin used differs if SWB will be used for outdoor or indoor products. In the case of outdoor use the solid content of the resin in the final product is 23%; in the case of indoor products this drops to 15.1% [4]. For the calculation it was assumed that the weight of the resin is more or less the same as the weight of the compressed bamboo, and has a similar weight in dry and wet states. This means that in the plank (FU) the amount of resin is 23% x 3.08 kg = 0.71 kg.

Input in LCA: Glue application

Type of glue	**Phenol Formaldehyde**
Weight/amount of glue	**0.71 kg/FU**

11. Pressing strips to beam

As a next step the glue-saturated strips are placed into a mold in which under very high pressure (2200 tons) the strips are compressed into beams of 190 x 11 x 14 cm by a cold press [3]. The power of the very large press deployed is estimated to be five times the power of the cold presses used for board production: 5 x 5.5 = 27.5 kW. It takes around 5 minutes for all the strips to be allocated, pressed and taken out of the press [3]. This means that 12 beams are produced per hour. Per beam, 8 planks can be made, corresponding to a production of 12 x 8 = 96 FUs per hour. This means energy consumption per FU for the press is 1/96 x 27.5 = 0.29 kWh/FU

Input in LCA: Pressing strips to beam

Energy consumption/FU	**0.29 kWh/FU**

12. Activating glue in oven

After pressing, the beams (which are still in the steel mold) will be located for 8 hours in a large oven where the glue will be activated at a temperature of 140-150 degrees Celsius [3]. The oven is assumed to have a capacity of 2 x 2 x 2 = 8 m3. To estimate the power of the oven used, the power of an industrial oven of approximately the same size as the one used in the SWB process was used for the calculation: 50 kW. It is expected that in the oven the beams (190 x 14 x 11 cm), which are still in the slightly bigger mold, would need a space of 0.2 x 0.15 x 2 meters each. This means 143 beams fit into the oven, corresponding to 1144 planks (FUs). Since a round takes 8 hours, 8 x 50 = 400 kWh is consumed per oven load. This means that per FU, 400/1144 = 0.35 kWh is consumed.

Input in LCA: Oven

Energy consumption/FU	**0.35 kWh/FU**

13. Sawing beams


In order to acquire beams of exact dimensions, the borders of the beams need to be sawn. Because of the hardness of the material it is likely that a stronger saw needs to be used than for Plybamboo production. Therefore, it is calculated with a saw with twice the power of the sawing machine used for Plybamboo production (2 x 5.5 kW = 11kW). Assuming from observations [3] that it takes 2 minutes to place the beam and saw the borders, 30 beams can be processed per hour, corresponding to 30 x 8 = 240 FUs/hour, which corresponds to 1/240 = 0.004 hour per FU. The energy consumption for sawing the beams per FU is then 0.004 x 11 = 0.044 kWh.

Input in LCA: Sawing beams

Energy consumption/FU	**0.044 kWh/FU**

14. Sawing planks


As one of the final steps, planks will be sawn from the beam. For the calculation it was assumed that here also a saw with twice the power of the sawing machine used for board production is required (2 x 5.5 kW = 11kW). Assuming from observations [3] that two pieces can be produced from the beam per minute (including allocation and handling of the beam), 60 x 2 = 120 planks can be produced per hour, which corresponds to 1/120 = 0.0083 hours per FU. The energy consumption for sawing the planks per FU is then 0.0083 x 11 = 0.091 kWh.

Input in LCA: Sawing planks

Energy consumption/FU	**0.091 kWh/FU**

15. Sanding planks
According to [1], 250 m2 3-layer board can be processed per hour with the sanding machine (55-90 kW). It can be assumed that sanding the planks will take a little longer since they do not consist of a single board but several pieces: 150 m2/hour. This corresponds to 150/0.19 (1.9 × 0.1) m2 per piece = 789 FUs/hour, which corresponds to 1/789 = 0.0013 hour/FU. Energy consumption per FU for the sanding machine is then 0.0013 × 72.5 = 0.094 kWh

Input in LCA: Sanding planks

Energy consumption/FU	**0.094 kWh/FU**

16. Transport from factory to harbor
After sanding, the boards are packed in containers ready for transport. For the assessment it was calculated with a 20-foot container which has standard internal dimensions of 5.90 × 2.35 × 2.39 meters (33.2m3) and a maximum load of around 30 tons (including weight of the container of 2.3 tons), which was transported by a 28-ton truck, over a distance of 300 km (factory in Huangzhou to Shanghai harbor). For larger trucks and for sea transport the eco-costs are usually calculated based on the eco-costs per ton km of a certain vehicle (empty return figures taken into account in the one-way distance). The amount of ton.km per FU is 0.0031 tons × 300 km = 0.93 ton.km/FU. Based on the eco-costs/ton.km of a 28-ton truck the eco-costs per FU can then be calculated.

Input in LCA: Transport from factory to harbor

Distance	**300 km**
Kind of transport	**28-ton truck**
Ton km per FU	**0.93 ton.km/FU**

17. Transport from harbor to harbor
Calculations for the environmental burden for sea transport are based on transport with a trans-oceanic freight ship in a 20-foot container, with a travel distance from Shanghai to Rotterdam of 19208 kilometers. For sea transport the eco-costs are usually calculated based on the eco-costs per ton.km of the boat used. The amount of ton.km per FU is 0.0031 tons × 19208 km = 59.6 ton.km/FU. Based on the eco-costs/ton.km of a 20-foot container transported by a trans-oceanic freight ship, the eco-costs per FU can then be calculated.

Input in LCA:

Distance	**19208 km**
Kind of transport	**trans-oceanic freight ship (20-foot container)**
Ton km per FU	**59.6 ton.km/FU**

18. Transport from harbor to warehouse
The distance from the Rotterdam harbor to warehouse in Zwaag, the Netherlands, is 115 km. For the calculation it is assumed that one 20ft container is transported by a 28-ton truck. The amount of ton.km per FU is 0.0031 tons × 115 km = 0.36 ton.km/FU. Based on the eco-costs/ton.km of a 28-ton truck the eco-costs per FU can then be calculated.

Input in LCA: Transport from harbor to warehouse

Distance	**115 km**
Kind of transport	**28-ton truck**
Ton km per FU	**0.36 ton.km/FU**

Results

All the input data of the various production- and transport activities found above, including the corresponding eco-costs and the resulting overall eco-costs is summarized in table A9 below. The eco-costs were added by the second author, dr. Joost Vogtländer, based on the Eco-costs 2007 database available through the website www.ecocostsvalue.com (Vogtländer 2008).

Table A9: Input data and results for the environmental impact assessment of one carbonized SWB plank

Process step	Amount	Unit	Eco-costs (€)/unit	Eco-costs (€)/FU	Eco-costs (€)/kg	%
1. Cultivation and harvesting from plantation Gasoline consumption	0.010	liter/FU	0.104	0.001	0.0004	0.1%
2. Transport from plantation to strip manufacturing facility; Eco-costs of a 5-ton truck (transport of 492.3 FUs)	30	km/truck	0.243	0.014	0.0045	0.9%
3. Strip making: Energy consumption	0.1	kWh/ FU	0.109	0.011	0.0035	0.7%
4. Transport from strip manufacturing facility to factory; Eco-costs of a 10-ton truck (transport of 1277.7 FUs).	600	km/truck	0.32	0.132	0.0429	8.2%
5. Rough planing: Energy consumption	0.66	kWh/ FU	0.109	0.072	0.0234	4.5%
6. Splitting strips in half	0.10	kWh/FU	0.109	0.011	0.0035	0.7%
7. Carbonization: Energy consumption	0.35	kWh/FU	0.109	0.038	0.0124	2.4%
8. Drying: Energy consumption	2.58	kWh/FU	0.109	0.281	0.091	17.4%
9. Crushing strips	0.17	kWh/FU	0.109	0.019	0.006	1.1%
10. Glue application: Added amount of Phenol formaldehyde (wet)	0.710	kg/FU	0.827	0.587	0.191	36.4%
11. Pressing strips to beam	0.29	kWh/FU	0.109	0.032	0.0103	2.0%
12. Activating glue in oven	0.35	kWh/FU	0.109	0.038	0.0124	2.4%
13. Sawing beams: Energy consumption	0.044	kWh/FU	0.109	0.005	0.0016	0.3%
14. Sawing planks: Energy consumption	0.091	kWh/FU	0.109	0.010	0.0032	0.6%
15. Sanding planks: Energy consumption	0.094	kWh/FU	0.109	0.010	0.0033	0.6%
16. Transport from factory to harbor Eco-costs (28-ton truck)	0.93	ton.km/FU	0.033	0.031	0.0100	1.9%
17. Transport from harbor to harbor Eco-costs (20ft container in a trans-oceanic freight ship)	59.60	ton.km/FU	0.0052	0.310	0.1006	19.2%
18. Transport from harbor to warehouse Eco-costs (28-ton truck)	0.360	ton.km/FU	0.033	0.012	0.0039	0.7%
Total eco-costs (€)				**1.613**	**0.524**	**100.0%**

Appendix B: Carbon Sequestration by Bamboo

In this appendix carbon sequestration by a permanent bamboo plantation is compared to a wood plantation. This calculation and its parameters are largely based on the annual yield calculation in chapter 3. Therefore, the calculation and the resulting tables are presented in a compressed manner in this appendix. Before the carbon sequestration for bamboo is analyzed in this appendix an introduction about global warming is provided, including the role of CO_2 with respect to this problem.

Introduction

Global Warming and the Role of Carbon Dioxide

Global warming is one the recent developments that will most likely have a high impact on our world in the coming ages. Although the exact consequences of global warming are unclear, it is expected that global warming may have a negative impact on the roots of sustainable development, and for the Planet component may impact the three main environmental problems: depletion of resources, deterioration of ecosystems and deterioration of human health (see table 1.1). For example, through global warming sea levels will most likely rise, which is expected to increase extreme weather (hurricanes) and precipitation patterns (droughts and floods), which, as a result may impact agricultural yields, ecosystems, resource supplies, etc.
The most important organization that investigates causes and consequences of global warming is the Intergovernmental Panel on Climate Change (IPCC). In its most recent assessment (2007) the panel concludes that "most of the increase observed in globally averaged temperatures since the mid-twentieth century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations." In other words, through human activity (industry, energy consumption, extraction of resources, agriculture, etc.) the concentration of various gases creating the greenhouse effect causing global warming has increased steadily during the last decennia. One of the most important greenhouse gases contributing to global warming is carbon dioxide (CO_2), followed by methane (CH_4) and ozone (O_3) (Kiehl and Trenberth 1997). Of these greenhouse gases, CO_2 is probably best known by the general public, since it is expected that combustion (burning of fossil fuels) through human activity has contributed to 75% of the increase of CO_2 concentration the past 20 years; the remainder is largely caused by changes in land use, in particular due to deforestation (IPCC 2001).
It is for these reasons that CO_2 has received much attention as a greenhouse gas, and carbon sequestration by plants and trees is increasingly promoted as an important policy instrument against global warming, although there is increasing debate about the effectiveness of these measures due to the often temporal effect of carbon sequestration in this manner.

During their growth, trees (and other plants including bamboo) convert CO_2 (and water) through photosynthesis into carbohydrates, and emit oxygen in the process. The tree uses these carbohydrates to form cellulose and lignin cells, which contain carbon atoms, and thus store the carbon for the lifespan of the tree. The carbon makes up approximately half of the dry weight stored in the wood of the tree (Birdsey 1996). Thus, the higher the dry weight of the tree, the more carbon is stored in the wood of the tree. The carbon will be stored in the living tree, but will also remain stored once the tree is felled and the wood of the tree is used for durable products. When the tree dies or the product in which the wood is used is dumped, the carbon will be released again into the atmosphere in the form of CO_2 for example, through decay or incineration. This means that in essence the use of renewable materials such as wood can be perceived as a CO_2 neutral material (if CO_2 emitted during production and transport is not taken into account). Note that as an end-of-life scenario incineration of the material is preferred over landfill, since in the latter scenario the greenhouse gas methane may be released, which is expected to be over twenty times more harmful as greenhouse gas than CO_2 (Hammond and Jones 2006). Since the chemical composition of bamboo and wood is nearly identical (Liese 1998) it is assumed that per kilogram of resource or material, bamboo and wood contain a similar amount of carbon in their tissue.

Base of Comparison and Main Assumptions

The carbon sequestration comparison was made for bamboo- and wood plantations, which have a lower standing volume than natural forests, but usually a higher yield. A hectare of sustainably managed bamboo- or wood plantation will sequester CO_2 in two ways: first, through the standing volume of plants (which will remain living and have a steady biomass in the case of good plantation management), and second, through the fixation of carbon in products. For this calculation it was assumed that the resource will be used for the manufacturing of durable products, i.e. products with a life span of at least 20 years (e.g. flooring, furniture). Note that there will also be carbon fixated in products that are less durable[25]; however, in this calculation this amount of stored carbon is not taken into account. In case there is a constant yield of bamboo- or wood material, which is continuously fixated in durable products, the additional amount of carbon sequestered by durable products can be added to the carbon fixated in the permanent plantation. Note that the carbon sequestration is only relevant if the plantation will remain standing and keep producing. If this is not the case the carbon captured by the plantation and/or in the products will in time be released again to the atmosphere in the form of CO_2. The calculation is based on carbon sequestered in semi finished materials, similar to the annual yield calculation (see section 3.2).

[25] For bamboo, for example, chop- or match sticks (expected life span of less than a year) or curtains (expected life span of less than five years).

Results

Carbon Stored by the Standing Volume of a Plantation

In table B1 the average standing volume (in m3) of an established wood plantation is presented, based on which the amount of tons of carbon stored in the plantation can be determined. Note that the carbon stored in a natural forest is usually significantly higher than in a plantation. For example, the biomass stored by a hectare of tropical rainforest may account for up to 330 tons carbon (Sundquist 2007).

Table B1: Estimates of the carbon stored in a hectare of wood plantation for various species (Kuiper 2006, van Straten 2006)

Wood species	Total standing volume (m3/ha)	Density (kg/m3)	Total dry weight including roots (tons/ha) [26]	Carbon stored per hectare including roots (tons/ha)
Baby Teak	300	700	262.5	131
Regular Teak	350	700	306	153
European oak	312.5	700	274	137
Eucalyptus	350	500	218	109

Since there are no figures of the carbon storage for Moso plantations, these figures had to be based on the carbon storage of a natural Moso stand. Isagi (Isagi et al. 1997) found the biomass of a natural stand of Moso in the neighborhood of Kyoto, Japan to measure 182 tons/ha (dry weight), of which 44.6 tons (24%) was stored in the part of the plant below the ground (roots and rhizomes) and 137.9 tons (75.6%) was stored in the parts above the ground (mainly in the stem; 116.5 tons). Isagi et al. (1997) noted that "the total above-ground biomass measured is one of the largest among the world's bamboo communities." In a plantation, the number of stems per hectare will be reduced for a maximum yield of straight culms. For this calculation it was assumed that the number of stems will be reduced by 50% for a plantation compared to a natural forest, which results in a dry biomass weight of 182/2 = 91 tons per ha, which refers to 45.5 tons carbon stored per ha of Moso plantation.

Besides Moso, Guadua was also taken into account in this assessment. For Guadua some carbon sequestration studies were executed by Riaño et al. (2002) in sites reforested with Guadua in the river Cauca valley in Colombia. Six years after establishment, Riaño et al. found the total dry weight of the accumulated biomass to be 108.7 tons/ha, of which 21.6 tons (19.9%) was stored in the part of the plant below the ground (rhizomes) and 87.1 tons (80.1%) was stored in the parts above the ground (mainly in the stem; 79.1 tons). Since the plantation had not reached its mature phase yet, it is assumed for this calculation that the dry weight of the biomass would still increase with 33% to measure 144.5 tons, which equals 72.25 tons carbon stored in a hectare of Guadua plantation.

Table B2: Estimates of the carbon stored in a bamboo plantation (Isagi et al. 1997, Riaño et al. 2002)

	Total dry weight including roots (tons/ha)	Carbon stored per hectare (tons/ha)
Moso	91	45.5
Guadua	144.5	72.3

From the tables it can be concluded that depending on the species, a wood plantation in general stores (up to two times) more carbon in its standing volume than a plantation of giant bamboo species.
However, in these figures the establishment phase has not been taken into account. In case degraded land or grassland will be reforested, the establishment time of a plantation may also play a role in carbon fixation. While the establishment time of a (sub)tropical giant bamboo plantation 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) to 30 years (baby Teak) to 70 years (regular Teak) to 80 years (European oak) (Kuiper 2006, van Straten 2006). This means that in the early years a bamboo plantation will sequester more carbon than the standing volume of a wood plantation; however, in time the total carbon sequestration of a wood plantation will surpass the sequestration by the bamboo plantation.

[26] In the total dry weight an additional 25% is assumed to account for biomass stored below ground in the roots of the tree.

Carbon Stored in Durable Products

As was mentioned above, besides the fixation of carbon in the plants (trees/stems), in the case of a sustainably managed plantation, the increase in biomass of the plantation can be harvested, processed and used in durable products, through which an additional amount of carbon is stored. The annual yield in cubic meters of a semi finished material, based on which the sequestered carbon can be determined, was already established in section 3.2 annual yield for production scenarios A and B. If it is assumed that the products in which the wood or bamboo is used have an average lifespan of 20 years (after which the carbon stored in the product will be released again in the atmosphere), and the plantation will have a continuous output of material which will be used in durable products (which compensates for the carbon released by products that reach the end of their lifespan after 20 years), an additional amount of 20 times the annual carbon storage is sequestered in durable products per hectare of plantation (see tables B3 and B4).

Table B3: Estimates of the carbon stored in durable timber products sourced from a wood plantation (Kuiper 2006, van Straten 2006, Wiselius 2001)

Wood species	Scenario A: Annual yield in sawn timber (m3/ha)	Scenario B: Annual yield in MDF (m3/ha)	Density (kg/m3)	Annual yield in dry weight (tons/ha)	Carbon stored per hectare (tons/ha)	Cumulated amount of carbon stored in 20 years (tons/ha)
Baby Teak	4.4	N/A	700	3.1	1.55	31
Regular Teak	2.1	N/A	700	1.47	0.74	14.8
European oak	1.8	N/A	700	1.26	0.63	12.6
Eucalyptus	8.8	10.7	500	4.4	2.2	44
			750 (MDF)	8	4	80

Table B4: Estimates of the carbon stored in semi finished materials sourced from a bamboo plantation

Bamboo species	Annual yield semi finished material (m3/ha)	Density (kg/m3)	Annual yield in dry weight (tons/ha)	Carbon stored per hectare (tons/ha)	Cumulated amount of carbon stored in 20 years (tons/ha)
Moso: A-quality materials	Plybamboo: 2.0	700	1.4	1.9	38
	Taped mats: 1.5	700	1.1		
	SWB:1.2	1080	1.3		
	Total: 4.7		**Total: 3.8**		
Guadua: A-quality materials	Plybamboo: 3.9	700	2.7	3.6	72
	Taped mats: 2.9	700	2.0		
	SWB: 2.3	1080	2.5		
	Total: 9.1		**Total: 7.2**		
Moso: SWB	4.6	1080	5.0	2.5	50
Guadua: SWB	8.8	1080	9.5	4.8	96
Moso: B-quality materials (MDF)	5.4	1050	5.7	2.8	56
Guadua: B-quality materials (MDF)	10.3	1050	10.8	5.4	108

Total Carbon Fixation Stored by a Bamboo- and Wood Plantation

Based on carbon fixated by the permanent standing volume in the plantation, and carbon accumulated in durable products with an average lifespan of 20 years, the total carbon sequestered by a permanent plantation can be determined, which can be used to compare wood and bamboo (see table B5 and figure B1).

Table B5: Total carbon fixation by a hectare of an established plantation for various bamboo- and wood species

Species	Stored carbon per hectare in plants (tons/ha)	Cumulated amount of carbon stored in durable products in 20 years (tons/ha)	Total carbon fixation (tons/ha)
Baby Teak	131	31	162
Regular Teak	153	14.8	168
European oak	137	12.6	150
Eucalyptus	109	44	153
Eucalyptus (MDF)	109	80	189
Moso: A-quality materials	45.5	38	84
Guadua: A-quality materials	72.3	72	144
Moso: SWB	45.5	50	96
Guadua: SWB	72.3	96	168
Moso: B-quality materials (MDF)	45.5	56	102
Guadua: B-quality materials (MDF)	72.3	108	180

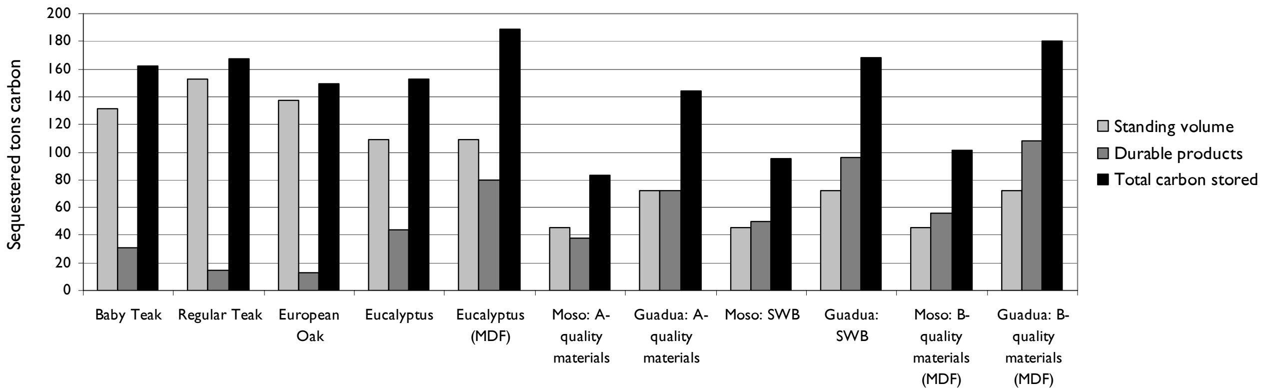

Figure B1: Total carbon fixation by a hectare of an established plantation for various bamboo- and wood species

From figure B1 and table B5 it becomes clear that whereas bamboo in general fixates more amounts of carbon in semi finished materials due to its high annual yields, wood fixates more carbon in the living plants on the plantation, which to some extent level each other out. From figure B1 it can be seen that in the case of an established Moso plantation no matter how the yield will be used (A-quality materials, SWB or MDF), the total carbon fixation per hectare is lower than for a permanent plantation of wood species. For a permanent plantation of the larger bamboo species, Guadua, the situation is different. If a Guadua plantation is used to produce A-quality materials, total carbon sequestration is slightly lower than most wood species. However, in the case of SWB or MDF production, carbon sequestration by Guadua may, due to the higher yields, be slightly higher than most wood species.

It should be noted that in figure B1 the long establishment times of slow growing hardwoods such as regular Teak and European Oak are not taken into account. As a result, in the case of reforestation, in the establishment time of the plantation a bamboo plantation will sequester more carbon than all wood species. Only in time, the wood plantation will catch up in total carbon sequestration.

From the above it can be concluded that the argument - often used by bamboo material producers - that bamboo will sequester more carbon than wood is not valid. From figure B1 it became evident that giant bamboo species such as Guadua can definitely compete in terms of carbon sequestration with the fastest growing hardwood species, but that materials made from the bamboo species most commonly used for bamboo materials used in the West, Moso, in total sequester less carbon than competing hardwood species. However, as was already mentioned in section 3.3, instead of carbon sequestration, the efficiency in annual yield should be the crucial criterion for crop choice of a hectare of vacant land in the future in order to meet the increasing demand for raw materials, which turns out more positively for bamboo compared to wood.

Photo Credentials

In alphabetic order:

Arjan van der Vegte	Figures: 1.5, 1.6, 1.8, 1.10 and 2.20, and all photos in appendix A (except material samples) and title page
Fasting Fotografie	Figures: 2.11 and 2.21
Jared Huke	Figure 1.9
Pablo van der Lugt	Figures: 1.7, 2.1, 2.3, 2.9, 2.13, 2.15, 2.16, 2.18, 3.1, 3.2, 3.8, 3.9, 4.1 (right) and 4.2, and photos of material samples in appendix A
Tejo Remy and René Veenhuizen	Figure 2.7
Unknown	Figures: 1.11, 2.4, 2.23 and 4.1 (left)

Abstract (PRINT ON BACK OF INBAR TECHNICAL REPORT NR 30)
Materials have a considerable impact on the environmental sustainability of the products in which they are used. Due to the increasing population and consumption worldwide, more raw materials are consumed than can be produced globally, making especially resource depletion of both abiotic and biotic resources an urgent problem. Due to its good properties and high biomass production, bamboo could have the potential to help meet the increasing demand for raw materials, especially as a substitute for scarce and slow growing hardwood.
In this INBAR Technical Report the environmental sustainability of various bamboo materials - based on consumption in Western Europe - are assessed based on LCA-methodology (Eco-costs) and annual yield predictions revealing if bamboo is actually a more environmentally sustainable choice than timber.