1 Introduction

This chapter provides an introduction into this PhD research.
In sections 1.1 and 1.2 the problem that has led to this dissertation is explored, first focusing in section 1.1 on the relevance of renewable materials as raw material input for sustainable products, including the need to look for substitutes for (hard)wood, such as bamboo. In section 1.2 the promising potential of bamboo as a sustainable renewable material is discussed, but also the obstacles leading to the low market share of bamboo in products in Western Europe are discussed. The low commercialization rate is targeted in this research through the active involvement of designers which is explained in section 1.3. Finally, sections 1.4, 1.5 and 1.6 respectively present the classification, scope and structure of this research.

1.1 Materials and the Environment

1.1.1 The Concept of Sustainability

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"[1], through a better balance in economy and ecology, the term "sustainability" was first mostly interpreted in its environmental meaning.

[1] In this research, the terms "North" (or "West") and "South" refer, unless stated otherwise, to countries classified according to their industrialization level, economical development, and Human Development based on the Human Development Index as developed by the United Nations (UNDP 2006). "North" and "West" are used to refer to developed countries, also known as industrialized countries or advanced countries, and "South" is used to refer to least developed countries, developing countries or newly industrializing countries, also known as emerging economies or markets, such as India and China (Bozyk 2006).

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	Depletion 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 Brundltand 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). For example, the 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 (see for example the EU greenhouse emission targets above), and there is a strong debate going on about strategies on the global level (e.g. Cradle to Cradle philosophy by McDonough and Braungart (2002)) about how to meet these environmental goals, the factor 20 environmental improvement has not come closer at all. In fact, environmental problems such as climate change caused by the emission of greenhouse gases such as carbon dioxide 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, leading to an increase in wealth and consumption per capita of these densely populated countries. Furthermore, 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).

In recent years, due to the increasing globalization, economical and social components - related to human rights, minimization of child labor, health & safety in the workplace, governance and management, transparency and the abolition of corruption and bribery - were integrated in the term

sustainability as well. 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).

Sustainability in Product Design

The increasing importance of sustainability has had a direct impact on product design[3] and product development[4] approaches. Every company develops products in the form of products or services that need to be sold in a profitable way to consumers who use the products. Because of the increasing importance of sustainability, new product design approaches incorporating sustainability issues have been developed in the last few decades.

Designers link the user with the product, and play a key role in the potential integration of environmental requirements over the complete life cycle in the design of their products (Charter and Tischner 2001). Products affect the environment during their complete life cycle, i.e. production, distribution, use and disposal. Unlike what was expected, in many cases, the last three phases have a larger environmental impact than the production phase. Initially, in the 1980s and 1990s this life cycle thinking was not taken into account when improving the environmental impact of products, focusing on

[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.
In this thesis the term "value chain" is used in combination with the term "Production-to-Consumption System" (PCS), which also adds the external environment to the value chain (see subsection 1.2.3).
[3] Product design entails "the whole process of the development of a new product within an enterprise including the description of the spatial and physical-chemical form of the product and the intended means of use" (Roozenburg and Eekels 1995). The product designer, referred to in this thesis as "designer", is the person who executes this process and translates requirements and needs of a commissioner into a concrete product (or service). Most product design is executed in batches or serial production using industrialized processes; therefore most product designers are also referred to as "industrial designers".
[4] Besides the design of the product, product development also entails the "development of the strategic course of the enterprise, the fabrication process, required machinery, the production organisation, logistics, marketing and the financing of the newly to be developed product" (Roozenburg and Eekels 1995). From the perspective of the designer the activity product development integrates marketing (e.g. market selection) and production planning with the design activities.

end-of-pipe technologies first before shifting to new concepts such as cleaner production and eco-efficiency (Crul and Diehl 2006).

The Design for Environment (DfE) approach (also known as Eco-design) developed in the mid 1990s was the first systematic product design approach that took the whole life cycle of the product into account in order to minimize the environmental impact (Graedel and Allenby 1995). Brezet and van Hemel (1997) presented eight DfE strategies to reduce the environmental impact of products during the complete life cycle: 1) selection of low-impact materials, 2) reduction of materials usage, 3) optimization of production techniques, 4) optimization of distribution system, 5) reduction of impact during use, 6) optimization of initial lifetime, 7) optimization of end-of-life system, and 8) new concept development (functional level).

While in the beginning Eco-design focused on product improvement or redesign (Berchicci 2005), it soon became clear that with optimization on product level only a maximum factor 2 improvement of the environmental impact could be reached. In order to come closer to the required factor 20 improvement more radical changes are needed on the functional or system level (see figure 1.1).

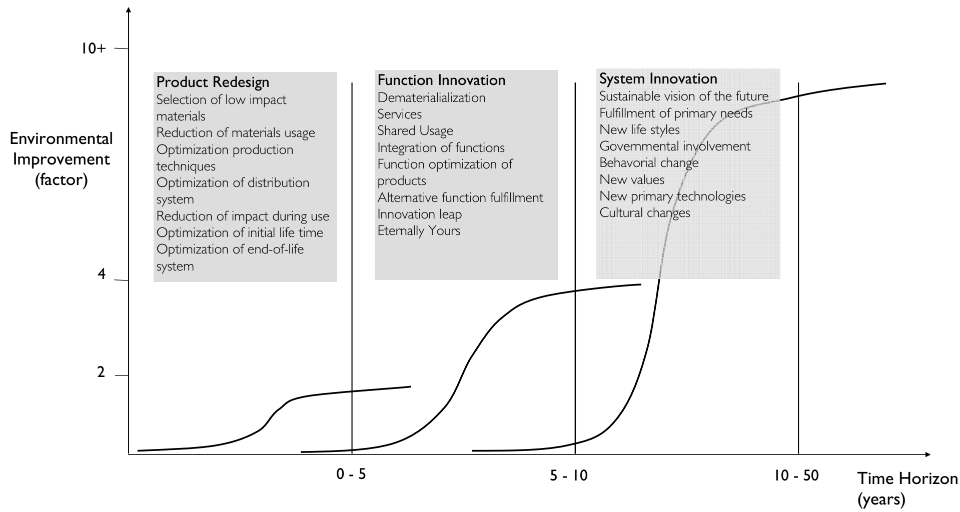

Figure 1.1: Potential level of environmental improvement in product innovation (Brezet and Rocha 2001, Crul 2003)

Innovation on the functional level not only focuses on the existing products, but zooms out to look for new products and services that can replace existing products to improve the environmental burden (e.g. shift from physical products to a dematerialized service). The Product Service System (PSS) thinking is a good example of this kind of innovation. A Product Service System can be defined as "a marketable set of products and services capable of jointly fulfilling the needs of the user" (Goedkoop et al. 1999). Various cases have shown that functional innovation can provide an environmental improvement of up to factor 4 (Mont 1999).

However, the factor 20 improvement can possibly only be reached on the system level, on the level of society as a whole. Because of its radical character, system innovation will take a lot more time than changes on minor levels, which may serve as stepping stones toward system innovation (see figure 1.1 above). System innovations can apply to different areas such as the social environment (new life styles), the infrastructure (new resource based distribution systems; e.g. the Distributed Economies philosophy) or the introduction of a new primary technology (e.g. shift to a hydrogen based energy economy) (Elzen et al. 2004).

While Eco-design has its focus on the environmental aspect of sustainability, Sustainable Product Design also integrates social and ethical considerations during the life span of the product (Charter and Tischner 2001), balancing the three elements of the Triple Bottom Line. This can be a tricky venture, because these elements can have conflicting interests; see figure 1.2.

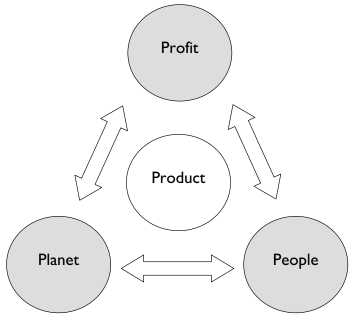

Figure 1.2: Finding the balance between People, Planet and Profit is the key issue in Sustainable Product Development (Crul and Diehl 2006)

This thesis focuses on the stimulation of a relatively unknown renewable material in the West (bamboo) because of its expected environmental sustainability for use in products in Western Europe, and does not actively take into account the potential value of the material in contributing to the socio-economic component of sustainability (Sustainable Product Design). Therefore, the subsection below about the role of materials focuses on the environmental sustainability.

1.1.2 The Impact of Materials on the Environmental Sustainability

The importance of materials in society throughout the history of man becomes evident in the classifications provided by archaeologists for various chronological eras: the Stone Age, the Bronze Age, and the Iron Age. Each age refers to the dominant material technologies being deployed at that time, recognizing the impact of materials on societal development and technological progress (Musso 2005). We may not be aware of it, but materials play a crucial role in our daily lives, or as Ashby and Johnson (2002) put it: "We live in a world of materials; it is materials that give substance to everything we see and touch." Through our senses, materials also have a large impact on the experiences people have with products (Jordan 2000). The materials used as input in products and buildings are usually referred to as "semi finished materials" or "trade materials" [5], referring to materials in standard dimensions provided by the supplying industry, that still require some level of processing (e.g. sawing, milling) before they can be deployed in a product (Eekhout 1997). Examples of semi finished materials or trade materials are glass sheets, MDF boards or steel I-beams in standard dimensions.

As seen above, 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

[5] Eekhout (1997) identifies the stages a material goes through before becoming a trade material as "raw material", "material" and "composite material". A raw material is a material before purification or processing, and as such is not directly applicable in industries (e.g. ore, clay, oil, cut trees). After purification or first rough processing a "material" is ready for industrial processing (e.g. cement, sand, logs, steel). If this "material" is not homogeneous and consists of two different materials (e.g. fiber reinforced polyester, reinforced concrete) it is referred to as "composite material". After industrial processing the trade material or semi finished material is developed. When the term "material" is used in the remainder of this thesis, it refers to semi finished materials.

and efficiency of production technology), use phase (e.g. durability during life span) and the end-of-life phase (e.g. possibility of recycling or biodegradation at the end of the life span). This shows that materials are intrinsically linked to every stage of the life cycle of a product. Furthermore, materials come early in the value chain: Because they stand at the base of many kinds of applications, materials usually serve as the first competitive point for differentiation in the value chain (Musso 2005). Finally, no matter what the level of system- or functional innovation will be in the future, unless the product is a service, materials will always be needed to materialize the new product.
If we look at the three main environmental problems introduced earlier, the important role of materials on the environment also becomes evident:

Depletion of Resources

Directly, through the extraction of renewable biotic (e.g. timber) and finite abiotic (e.g. minerals, oil) raw materials, but also indirectly (fossil fuel needed for the production of materials), materials contribute to the depletion of resources. Taking into account the high raw material consumption of industrialized countries per capita, which lies in the range of 45-85 tons per year[6] [7] (Adriaanse et al. 1997, Dorsthorst and Kowalczyk 2000), and the expected population and consumption growth in the coming decades (see factor 20 explanation before) due to the transition of emerging economies (e.g. India, China[8]) into industrialized countries adopting Western production and consumption patterns, it becomes clear that resource depletion is becoming an urgent problem for society. More than 70 percent of the raw materials that are used as input for industrial processes in the Netherlands are extracted from other places in the world (Adriaanse et al. 1997), showing that depletion of resources is truly a global problem.
There are also various experts that believe that resource depletion of abiotic resources such as minerals is not an immediate concern, and can be tackled through increasing production and exploration capacity as well as through technological advances, in particular through recycling (Tilton 2002).
However, late studies (Cohen 2007, Gordon et al. 2006) in which current mineral consumption figures (based on a steady demand, an equal production- and consumption rate and including win-back percentages through recycling) are projected to the future indicate the contrary (see table 1.3), predicting depletion times of many important minerals (e.g. lead, zinc, indium) within half a century. In the figures in table 1.3 the increasing demand by emerging economies and developing countries in the future is not integrated, which suggests the urgency of the problem is even higher. Gordon et al. (2006) warn that: "Virgin stocks of several metals appear inadequate to sustain the modern 'developed world' quality of life for all of Earth's people under contemporary technology," and although recycling rates may increase in the future, a large amount of the extractable metals in the Earth's crust such as copper (26%) and zinc (19%) are already lost in non-recyclable wastes (Gordon et al. 2006).

[6] For example, in Japan 14 tons of ore and minerals need to be mined and processed per capita annually to meet demand for cars and other other metal-intensive products (Adriaanse et al. 1997).
[7] 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% need to be primary (van den Dobbelsteen 2004).
[8] 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).

Table 1.3: Depletion times in years (reserve base/annual global consumption) of several minerals assuming global consumption equals global production (Cohen, 2007)

Mineral	Estimated depletion time (years)
Aluminium	1027
Chromium	143
Copper	61
Gold	45
Indium	13
Lead	42
Nickel	90
Platinum	360
Tin	40
Uranium	59
Zinc	46

Table 1.3 shows that basically man is extracting and consuming 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). Besides material resources, the Ecological Footprint also includes global food-, water- and energy production and consumption, including the required capacity to absorb the wastes emitted in energy generation (nuclear waste and CO_2 emissions during fossil fuel combustion) related to the environmental problem of ecosystem deterioration (see below).

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[9] 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 1.3). On the demand side the global population, the consumption per person and the average footprint capacity per unit of consumption (i.e. amount of resources used in the production of 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.

[9] 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.

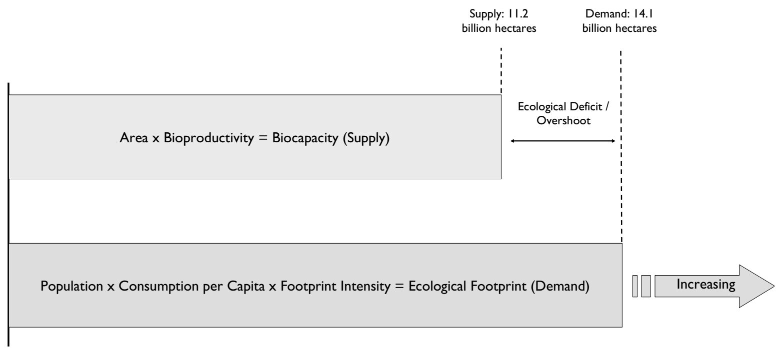

Figure 1.3: Gap between supply and demand between bioproductivity and Ecological Footprint (figure adapted after WWF International 2006)

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 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 thesis, 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. petroleum extracted in developing countries being processed to plastics in developed countries), or in the case of local production, usually flows back to owners in industrialized countries.

1.1.3 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 design is the deployment of renewable materials, as also proposed in the DfE strategy wheel (DfE strategy one) by Brezet and van Hemel (1997), and the Three Step Strategy[10] 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 due to their ability to regenerate and thus help meet 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. For example, 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 biofuels, stimulated until recently in various governmental policies to substitute fossil fuel because of their presumed ability to reduce emission of greenhouse gases, may even increase emission of these gases on the global level due to additional emissions caused by conversion of forests and grasslands to cropland. The example above shows that renewable resources per se are not automatically environmentally sustainable, and that global synchronized policies are required if the available productive hectares are to meet the future global human 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 assessed, before reviewing the potential of other renewable materials for raw material production.

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).

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[10] 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)

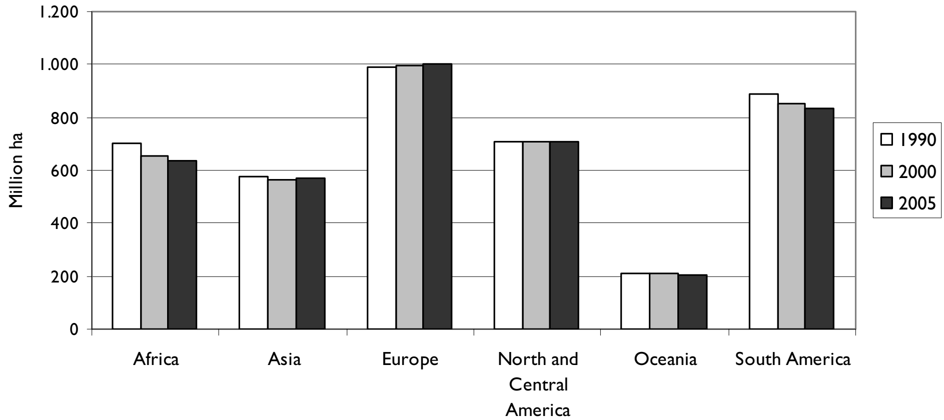

Figure 1.4: Trends in forest area by region[11] 1990-2005 (FAO 2006)

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).

Table 1.4: 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

[11] 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 1.4.

Although the total area of certified forests is growing, because of the high requirements resulting in complex logistics and management systems needed during the value chain, the availability of certified wood is low, whereas the demand is very high and is expected to remain growing, resulting in 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).

The Situation in (sub)Tropical Areas

From figures 1.4 and 1.5 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).

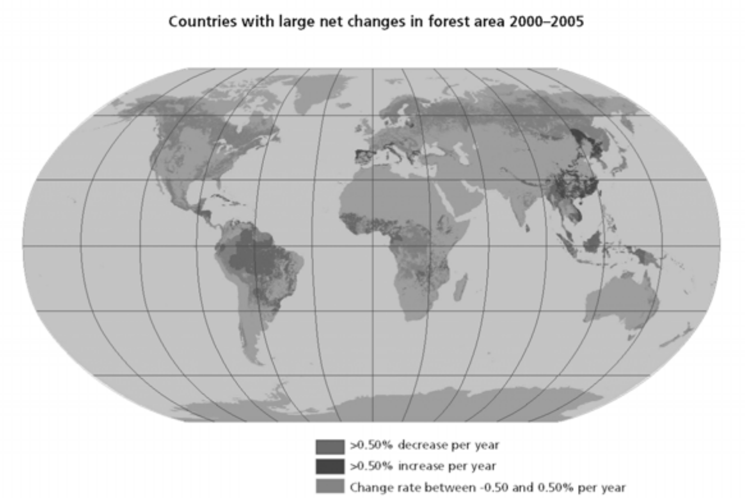

Figure 1.5: Changes in forest area worldwide 2000 - 2005 (FAO 2006)

The causes of tropical deforestation are complex and many. Various studies show that although wood production is an important factor in deforestation, deforestation is also 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 fulfill demand for food, man is turning to forest land reserves (required for housing, fuel and as carbon sink).
While the total forest area in the (sub) tropics is 858,842 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 an urgent 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 NWFP 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 thesis the potential of bamboo, as one of these relatively unknown renewable materials, is explored because of its high potential for regeneration and thus also for raw material production.

1.2 The Latent Potential of Bamboo

1.2.1 Introduction about Bamboo

Virtues of Bamboo

Because of its high growth rate and easy processing, bamboo is a promising renewable resource that could potentially especially substitute for slow growing hardwood. Bamboo's good mechanical properties, low costs, abundant availability in developing countries and potential use in a multitude of applications show the potential of this versatile resource for income generation through commercialization of the resource. Moreover, because of its rapid growth and extensive root network, bamboo as a plant is a good carbon fixator, erosion controller and water table preserver. The bamboo plant is an eminent means to start up reforestation, as the plant often has a positive effect on groundwater level and soil improvement through the nutrients in the plant debris. In the box below a more general introduction about bamboo as a plant is provided.

Box: Bamboo as a Plant

From a botanical point of view, bamboo belongs to the grasses, the Graminea, and is therefore not a tree. Bamboo is a collective name of all botanical species. Although the complete taxonomy of bamboo is still evolving, current estimations are that around 1000-1500 different species of bamboo exist. There are considerable differences between species (see figure 1.6) in size, color, node distribution and configuration, mechanical properties and climatic preferences. Some giant species might reach up to 30 meters with cross sections of up to 30 centimeters per stem, whereas some species might not reach above 1 meter in height and 1 centimeter in diameter. Approximately 50 bamboo species are considered to be very suitable for use as construction material.

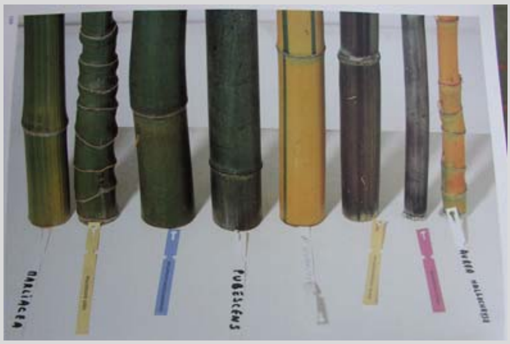

Figure 1.6: Various bamboo species

Bamboo is mainly distributed in countries with a tropical to subtropical climate. In Western countries bamboo is mostly known as a garden plant. Some smaller species can even withstand temperatures below zero, such as the species that live in the Himalaya mountains. Giant bamboo species, which have the most potential for industrial processing and economic development, mainly derive from (sub)tropical areas, usually in developing countries or emerging economies. In China and India the largest stocks of the worldwide 20 million hectares of bamboo forest can be found.

Figure 1.7: The bamboo species Phyllostachys Pubescens (Moso) can reach up to 15 meters (left) and grows abundantly in China (right), where a couple of million hectares of bamboo are available

Although the chemical compositions of bamboo and wood are practically identical (Liese 1998), the differences in anatomical composition are considerable. For instance, bamboo has no rays or knots. Furthermore, the bamboo stem is hollow compared to the solid stem of trees. In the cross section of a bamboo stem we can identify cellulose fibers (40%), vascular bundles (10%), and the in-between parenchyma tissue (50%), which largely consists of lignin (see figure 1.8). The fibers and the parenchyma tissue together function as a composite material: the cellulose fibers make the bamboo strong, functioning as the reinforcement in the matrix of the thin-walled parenchyma cells, similar to steel in reinforced concrete. The fibers run in a longitudinal direction around the vascular bundles. The outer wall of the stem consists of a thin silica layer of 0.25 mm that protects the stem. The outer and inner walls of the stem are also covered with a waxy layer. The solid patches (see figure 1.8) are the cross-sections of the cellulose fibers. The distribution of fibers increases from the inside toward the outside, where they are most needed with respect of moments of force that need to be absorbed caused by mechanical loads. After about 4 years, the walls of the fiber cells have become mature and solid. Only then is the bamboo stem ready to be felled for construction purposes. For applications in which the fiber function is less important (such as bamboo pulp for the production of paper), the stem can be felled at an earlier stage.

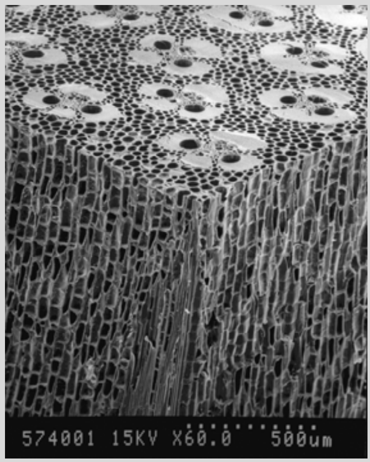

Figure 1.8: Microscopic three dimensional representation of bamboo tissue consisting of parenchyma cells, vascular bundles (black) circled by fibers (light and solid)

The greatest advantage of bamboo is undoubtedly its unparalleled 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), one of the major contributors to the greenhouse effect, causing global warming. 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 J this topic is further elaborated upon.

Besides the many traditional applications for local markets and low end export markets in which bamboo in its natural form (stem) is usually used, through industrial processing a wealth of new bamboo materials, such as Plybamboo and Strand Woven Bamboo have become available since the 1990s, which can be used for applications in high end markets in the West as well. In figure 1.9 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 1.9: Range of bamboo applications possible, based on traditional and advanced technologies (Larasati 1999)

In this subsection, 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). In the main introduction figure of chapter 5 on page 116 in the form of a collage, the production process of Plybamboo is depicted in short form (for the complete production process the reader is referred to appendix I). Besides flooring and board materials, China is also a major producer of woven bamboo mats that can be used, for example, in blinds.

Figure 1.10: 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 1.11 (left): Coarse woven mats form the building stones for BMB
Figure 1.12 (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 section 5.2). 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).

Figure 1.13: Application of SWB in a stairway

Recently, new higher resin content versions of SWB were developed apt for outside use[12], which could make SWB a suitable alternative for scarce tropical hardwood species such as Bangkirai. In table 1.5 the hardness of Plybamboo and SWB flooring are compared with various kinds of wooden flooring.

[12] 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 (Zaal and van der Vegte 2008).

Table 1.5: Janka hardness ratings for wood and bamboo flooring (after de Bruijn 2007a)

Wood/bamboo material	Janka Hardness (lbf) [13]
Douglas Fir	660
Yellow Pine	690 - 870
Teak	1000
Black Walnut	1010
Plybamboo (carbonized)	**1180**
Red Oak (Northern)	1290
White Oak	1360
Australian Cypress	1375
Plyamboo (natural)	**1380**
Hard Maple	1450
Wengé	1630
Brazilian Oak	1650
Merbau	1925
Burma Mahogany	2170
SWB	**2800**
Camaru (Brazilian Teak)	3540
Brazilian Tiger Mahogany	3840

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).

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 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.

Figure 1.14: Coiling is a non industrial processing technique that can create surprising effects; chair design (right) by Jared Huke

[13] The Janka test is a test method following ASTM (American Society for Testing and Materials) standards which is often used to establish the hardness of a wood species; it measures the force (in pounds force - lbf) required to embed a 11.28 millimeter steel ball into wood to half its diameter.

The Sustainability of Bamboo

Because of its widespread availability in developing countries, bamboo offers many opportunities for sustainable development, especially in developing countries where this development is needed most. Furthermore, bamboo can easily be processed manually or industrially, and due to its abundant availability has a low cost.

At an environmental level (Planet), due to its high growing speed, bamboo is expected to be an environmentally friendly material. Environmental impact studies based on Life Cycle Assessment (LCA) previously executed by the author have shown that the use of bamboo stems of the *Guadua spp.* species from Costa Rica used as a structural element (beam, column and rail) in a walking bridge in the Netherlands has led to a strong environmental improvement compared to common building materials such as steel, concrete and wood (van der Lugt et al. 2003). Although there is an extensive production process (many production steps), the environmental advantage for industrial bamboo materials such as Plybamboo was shown in the study to be on a similar level as most wood-based boards; due to the high resource production industrial bamboo materials may still serve as an excellent alternative compared to hardwood products (note that the environmental impact of bamboo materials will be assessed again in a more extensive manner in this research and presented in chapter 5).

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 (see figure 1.2).

Despite its evident virtues, bamboo is still regarded as an inferior material or as "poor man's timber" in developing countries (von Vegesack and Kries 2000). The ready availability and affordability of bamboo have had a negative effect in these countries. As many poor people live in bamboo houses, bamboo is easily associated with poverty. Although bamboo houses are very earthquake-resistant, many people in developing countries have, for reasons of social status, a preference for much less earthquake-resistant concrete dwellings.

Bamboo as an Alternative for Hardwood

In the previous subsection 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 1.6), and the decreasing forest areas (see previous subsection), 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 1.6: 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 x bioproductivity = biocapacity; see figure 1.3) 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.[14]

Figure 1.15: 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 (see table 1.5 above) 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.[15] 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

[14] Consumer products that yield services or utility over time rather than those that are completely consumed at once (Baxter et al. 2003).

[15] The annual yield of bamboo compared to hardwood is separately investigated in section 5.2 of this thesis.

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 thesis focuses on the potential of bamboo to help meet the demand for raw materials (and especially hardwood) in products in the West, and in particular on Western Europe as a consuming region.

1.2.2 The Market Share of Bamboo in the West

The annual world trade in bamboo and rattan has been estimated at $14 billion, although the current officially registered volume is $2.5 billion (Hunter 2003, Lobovikov 2003).[16] This shows that the importance of bamboo as a commodity on a worldwide scale is on par with other important commodities such as bananas ($5 billion) and cotton ($6 billion) (Hunter 2003, Lobovikov 2003). However, despite its promising potential, the market for bamboo products in Western markets like the USA and the EU is still small at the moment compared to the consumption of wood in products (Belcher 1999, Held and Manzano 2003, Klop et al. 2003, Mathew 1998). This was further amplified in an extensive market survey (van der Lugt and Lobovikov 2008) conducted by the author in collaboration with Dr. Maxim Lobovikov, chief of the Forest Product Service at FAO and former INBAR director. Some of the main conclusions of this market analysis showcasing the relatively small market share of bamboo products compared to wooden products in the West are presented below:

- Even compared to the size of only primary wood products (logs, sawn timber, veneer, and plywood), world trade in all bamboo products still pales in comparison. For example, the current value of global trade in all bamboo products is estimated at $2.5 billion, which is almost met by the value of the import of primary wood products in the Netherlands alone at $1.8 billion in 2004.
- The import of wooden furniture only for the Netherlands in 2002 ($1 billion) is almost as high as the import of bamboo and cane furniture parts (based on HS codes 9401.50 and 9403.80) over the whole world ($1.3 billion).
- With an estimated consumption of 0.67 million m2 in 2003, the bamboo flooring market represents a marginal role accounting for 0.7% of the wooden flooring market in the European Union (95 million m2). The same applies to the consumption of bamboo veneer in the EU (345 m3 in 2005), accounting for 0.019% of the consumption of wooden veneer (1,753,000 m3 in 2005).

With an estimated consumption of 0.67 million m2 in 2003, the bamboo flooring market represents a marginal role accounting for 0.7% of the wooden flooring market in the European Union (95 million m2). The same applies to the consumption of bamboo veneer in the EU (345 m3 in 2005), accounting for 0.019% of the consumption of wooden veneer (1,753,000 m3 in 2005).

Analysis of trade statistics shows that the current market size of traditional bamboo products is rather small. Only three product groups have a considerable size: (1) basketwork, (2) seats made from rattan, bamboo and similar materials, and (3) cane furniture made from rattan, bamboo and similar materials.[17] These traditional products mostly target saturated low end markets and have little growth potential, as the consumption figures over the last ten years show (INBAR 2008).

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[16] This difference between estimates and official numbers shows that the current set of the Harmonized System (HS) codes for bamboo products is insufficient for a detailed trade analysis. The existing HS codes represent traditionally plaited or cane based bamboo products and exclude new industrial bamboo materials. The new codes for industrial bamboo products, approved by the World Customs Organization, and effective since 2007, will make future bamboo trade statistics more reliable and precise (van der Lugt and Lobovikov 2008).

[17] For example, imports of basketwork between 1989-2002 in the USA were registered to be at a level of almost 300 million dollars annually ($295,793,000), while annual imports in the same period of cane furniture accounted for $231,055,000, and bamboo and rattan seats accounted for $100,824,000 (van der Lugt and Lobovikov 2008).

In contrast, new industrial bamboo products, such as flooring, veneer and board materials, show high growth potential. For example, the consumption of bamboo flooring increased approximately 25% between 2003 and 2005, while many other new materials, such as veneer, have successfully established a niche market in the West since its launch a couple of years ago (van der Lugt and Lobovikov 2008).

Although the actual market size of bamboo products is small compared to the wood market, because of their similar properties especially industrial bamboo materials could try to fill the increasing gap between supply and demand for hardwood.
However, before an intervention can be developed that may help to grasp this latent potential in practice, it is important to understand which obstacles along the value chain have caused the small market share of bamboo in products in Western Europe.

1.2.3 Obstacles during Bamboo Commercialization

Before the main obstacles causing the small market share of bamboo in the West are presented, some important concepts in new material commercialization need to be introduced first.

Obstacles in the Production-to-Consumption System; Materials in General

The commercialization[18] process is similar for most new materials and seems to follow a distinct pattern. Based on the work of Ashy and Johnson (2002) and Manzini (1986), van Kesteren and Kandachar (2004) acknowledge three sequential phases during the commercialization of a new material: the development phase, the introduction phase and the acceptance phase.
In the *development* phase, the material producer is the most important stakeholder. In this phase a new material is invented, tested and optimized by material technologists and scientists in terms of material properties, processing behavior and suitability for large scale production. In this phase the material might be tested in demonstration projects. Once the quality of the material is stabilized and the material can be produced in sufficient quantities, the material enters the *introduction* phase. During the introduction phase, designers start to use the new material for their products, and the first products become available for early adaptive consumers. During the implementation of the new material in products, knowledge is generated by the various stakeholders along the value chain (value chain nodes) with respect to the properties of the material during processing, production and use. Based on feedback from the field, the material might be further optimized by the material producer, and in the case of a positive evaluation this might result in growing adoption of the material by the other value chain nodes. Once the material becomes widely adopted in a certain market, the material has reached the *acceptance* phase in that sector.
Note that if sectors are adjacent to each other, and have similar stakeholders in the value chain with the same interests (e.g. might keep an eye on developments in the adjacent sector for example through magazines and symposia) a material might spread from one sector to another directly in the acceptance phase without a lot of additional efforts from the material producer (e.g. from the furniture sector to architecture). However, a material that is in the acceptance phase in one sector (e.g. titanium in the aerospace industry) can still be in the introduction phase or even development phase for sectors that are very different (e.g. titanium in the bike industry).
Although almost every new material goes through this process, there are large differences in time required to reach the acceptance phase (see table 1.7), while some materials might not even reach the market and will never leave the laboratories of material producers (van Kesteren and Kandachar 2004). Based on past experiences during the commercialization process for most materials, stakeholders in the

[18] The development and successful market implementation (realization) of a new product, service or material by a company (Roozenburg and Eekels 1995). In this thesis (product) innovation is perceived as synonym for commercialization.

materials industry acknowledge a typical 20-year interval between the invention of a new material and its widespread adoption in a certain sector (Musso 2005).

Table 1.7: Duration of the commercialization process from start of invention to widespread adoption for various materials (Maine and Garnsey 2006, Maine et al. 2005, van Kesteren and Kandachar 2004)

Name of material	Duration of commercialization process
Bakelite	25 years (1907 - 1932)
Nylon	4 years (1935 - 1939)
Teflon	23 years (1938 - 1961)
Polycarbonate	17 years (1953 - 1970)
Polypropylene	37 years
Kevlar	17 years
Carbon fiber	34 years

To better understand the causes of the long commercialization times of new materials one should look at the value chain of materials, which refers to the value addition through an activity in each node of the chain when bringing a product from conception (upstream[19]) to final use (downstream). The various activities in the value chain of raw materials into products are executed by different companies. As a reference in figure 1.6 in simplified form a typical value chain of a material that is being used in a consumer durable is presented. At the top of the figure the value adding activity is depicted and in the rectangles the main stakeholder that usually takes care of this activity in the value chain is represented (value chain nodes). If nodes are connected this means there is a direct interaction between nodes through material-, information- and/or money flows.

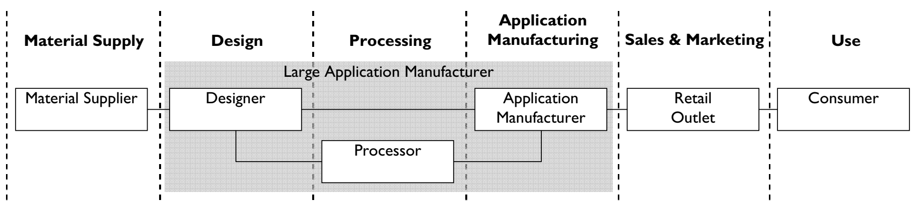

Figure 1.16: Simplified model of a typical generic value chain of a consumer durable

Although not depicted in figure 1.16, stakeholders in the external environment (e.g. government, NGOs, industry and trade organizations, etc.), that do not directly belong to the value chain, can also influence the adoption of materials in value chain nodes (e.g. through the development of regulations & policies or influencing public opinion). For this reason the Production-to-Consumption System (PCS) framework developed by Belcher (1995, 1999) was adopted in this thesis for obstacle analysis during the commercialization of new materials, including bamboo. A PCS is defined as "the entire set of actors, materials, activities and institutions involved in growing and harvesting a particular raw material, transforming the raw material into higher-value products, marketing and selling the final products to consumers." The system includes the technologies used to grow and process the material, as well as the social, institutional and economic environment in which these processes operate" (Belcher 1999).

[19] Upstream refers to stakeholders at the production side (closer to the source). Downstream refers to stakeholders closer to the consumption side of the chain.

While most materials differ in properties, many share similar problems during their commercialization process, as the influence flow model[20] in figure 1.17 shows. The model summarizes key obstacles found along the PCS during the commercialization of new materials in consumer durables in the North based on a review of relevant literature. Each obstacle adds costs directly or indirectly (e.g. time loss) to the commercialization process of the material and in the worst case can stop the commercialization of the material. For the obstacle analyses in this thesis, the use phase (including maintenance & recycling) of the consumer durable was added to the PCS. Below the model, the direct value chain nodes, which are influenced by the obstacles, are depicted. Dotted ovals can be considered obstacles on the meta level, which consist of various obstacles. For the background of each obstacle including literature references the reader is referred to appendix B.

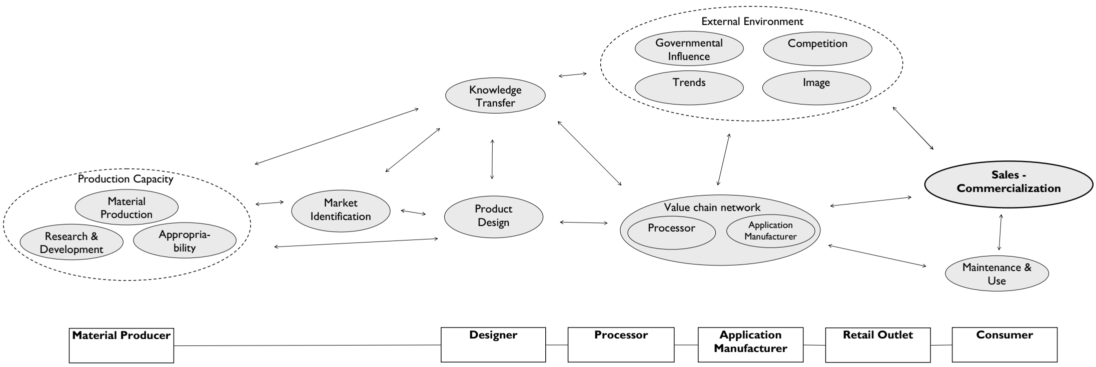

Figure 1.17: Influence flow diagram representing the main obstacles, and their relationships, over the PCS during the commercialization of new materials in consumer durables in the North

In general, the obstacles have a sequential relationship; it does, for example, not make sense to solve design related problems, if problems related to production capacity have not yet been solved. If a material is still in the development phase, the emphasis of problems will usually lie on the first part of the PCS (left side of figure 1.17), mostly related to the material producer. If a material reaches the introduction or acceptance phase, most problems during the commercialization of a new material will apply to value chain nodes downstream, on the consumption end of the PCS (right side of figure 1.17).
Furthermore, it should be noted that while some problems only apply to a certain value chain node (e.g. production capacity to the material producer), other obstacles may apply to more than one value chain node (e.g. knowledge transfer to all value chain nodes). Finally, the importance of the found obstacles may differ per material and sector (e.g. in the building industry governmental influence through codes & standards are very important for new materials to comply with).

Obstacles in the Production-to-Consumption System; Bamboo

Obstacles along the PCS during the commercialization of bamboo as a new material[21] in consumer durables (with a focus on the furnishing sector) for the Western European market are also similar to the

[20] In an influence flow diagram, qualitative relationships of a systemic nature that together influence an outcome can be depicted. The interactive nature of the relationships is shown in two sided arrows, showing the variable may operate both as cause and effect (Wolstenholme 1990).

[21] Note that especially industrial bamboo materials, due to their recent introduction and the corresponding relatively low acquaintance of value chain nodes with them, are perceived as new materials within this thesis. Furthermore, besides acquaintance of their use in low end traditional applications, knowledge about the real potential of the bamboo stem is also limited, and in a way the stem can also be perceived as a new material.

generic obstacles found in figure 1.17, as several separate field studies (van der Lugt 2005a, van der Lugt and Otten 2007) executed by the author in 2005-2006 in South East Asia (China) and Latin America (Ecuador & Colombia) as the producing region in the South, and Western Europe (the Netherlands & Germany) as the consuming region in the North, showed. In figure 1.18 the main obstacles found along the bamboo PCS based on design and production of products in the North (scope of this thesis) are summarized in an influence flow diagram. For the background of each obstacle including a more extensive explanation of the methodology used, the reader is referred to appendix C.

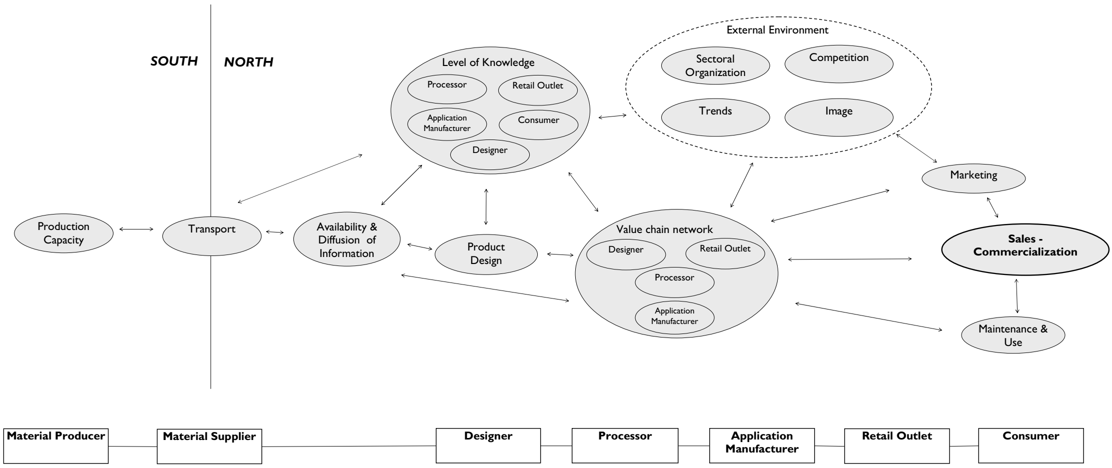

Figure 1.18: Influence flow diagram representing the main obstacles, and their relationships, over the bamboo PCS based on design & production of the products in the North

From the diagram it becomes clear that many different obstacles, related to various actors, with a complex cause and effect relationship hinder the successful commercialization of bamboo in consumer durables in Western Europe. Although there are many similarities between obstacles for generic materials and bamboo, there are also some differences. For example, for bamboo the image[22] problem is a larger issue than for most other materials (for more background information about the image problem of bamboo the reader is referred to appendices C and E). Furthermore, since bamboo is a natural resource, the production capacity obstacle has a different character than for more engineered materials such as plastics and metals, consisting of various (modified) resources.

Since the bamboo materials industry in the North is still relatively small compared to incumbent materials, obstacles for bamboo suppliers will be mostly similar to obstacles experienced by small generic material producers which have lower resources in terms of capital, facilities and client base compared to large material producers (see also subsection 1.3.1 below).

1.3 Using Designers to Stimulate Bamboo Commercialization

In the previous subsection an overview was provided about obstacles along the PCS that hamper the commercialization of bamboo in consumer durables in Western Europe, including the value chain nodes that affect these obstacles, resulting in the small market share of bamboo in products in Western Europe. This PhD thesis, deriving from the Faculty of Industrial Design Engineering of DUT, focuses on

[22] In this thesis the image of a material refers to the intangible properties of a material (Karana et al. 2008) i.e. the perceptions, associations and emotions related to a material. For more information about intangible properties the reader is referred to appendix D.

the potential role of the designer, as one of these value chain nodes, to stimulate the commercialization process.

1.3.1 The Potential Role of the Designer as Material Champion

In a social system - in this case stakeholders active in the nodes of the materials value chain - some persons have a more important role in the diffusion of an innovation than others. Rogers (2003) defines innovation as "an idea, practice, or object perceived as new by an individual or other unit of adoption." In the line of this research new materials can also be perceived as an innovation. Diffusion can be defined as "the process in which an innovation is communicated through certain channels over time among the members of a social system" (Rogers 2003).
For the adoption of a new material all the relevant members in a social system (value chain) need to be convinced before a material might make it eventually onto the final consumer market. The key persons involved in the diffusion of a generic innovation in a social network are opinion leaders or champions (Rogers 2003). *Opinion leaders* play a crucial role in the initiation of the diffusion of innovations through a social system. They are individuals that, in an informal way, have a high influence on the attitude and opinions of other individuals in a social system. *Champions* are for an organization what opinion leaders are for a community. A champion is usually a charismatic person who plays an important role in overcoming resistance in an organization toward the adoption of an innovation, or leads opposition against the adoption of an innovation (anti-champion). Since opinion leaders and champions have such similar characteristics and this thesis mostly relates to organizations, in the remainder of this thesis only the term "champions" will be used. Below, it will be explained that under some particular circumstances designers may function as a champion for the commercialization of a new material.

Although material research derives mostly from the defense and aerospace industry, it is now more directed at the consumer than before. This has provided the (product) designer a more important role in the adoption of new materials (Ashby and Johnson 2002). Designers have an important position in the value chain of most consumer durables because they link material producers with application manufacturers and potentially final consumers by translating the opportunities posed by a material in a concrete marketable product (Bas 2007, van Kesteren and Kandachar 2004).
Designers create products for various consumers who can choose from a high variety of similar products in a competitive market. For these reasons the user-interaction aspects of a product are very important as well for these consumers; besides technical and functional benefits, emotional benefits are also required to compete in the market (van Kesteren 2008). Therefore, alongside the technical and economical properties of materials, designers also integrate the environmental-, use-, as well as softer[23] sensorial- and intangible properties of materials in their designs. For more information about the role of materials in product design and an explanation of various material properties, the reader is referred to appendix D.
In industries where material costs sensitivity[24] is high (low end consumer goods, building industry) or technical constraints prevail (aerospace engineering), the role of the designer might be replaced by a production technician or engineer. In contrast, in medium to high end markets for most consumer durables (e.g. furniture, sport equipment, domestic appliances, consumer electronics) next to the

[23] Material properties that have a subjective character and depend on the perception of the beholder: sensorial properties and intangible properties of materials.
[24] Material costs sensitivity refers to the influence material cost has on the overall cost of a product (Ashby and Johnson 2002). If a lot of value is added in the processing and development of a material the product in which the material is used is material - cost insensitive (compare a golf club with a lot of added value, to a golf tee, which is a very material - sensitive product because of the low added value).

technology and functional aspects, user-interaction aspects are also of importance, facilitating a more important role of the designer as material prescriber.

In medium to high end consumer durables markets, usually small to medium sized (SME)[25] material producers are more innovative than large material producers and are the players to introduce new materials (Maine et al. 2005). Large material producers often focus on bulk low end mass markets or follow a market pull approach in medium to high end consumer durable markets in which they, based on their reputation, large resources, extensive existing client base, and marketing competences, focus on meeting the needs of existing clients through delivering service, quality and developing improvements to established materials by adding specific utilities required by the client. When large material producers do develop new materials, they are usually based on incremental innovations of established materials, pushed into the market by convincing their existing clients (large application manufacturers) of the virtues of the new material by organizing master classes in which all relevant departments that have an influence on the adoption of the material (design, production, marketing, purchasing, and management) are invited (Bogaert 2007, van Rijn 2007). However, due to the desire to match research & development activities strongly with current core competencies and the priority with many large material producers to safeguard current business, many potentially profitable markets are passed over by them (Maine et al. 2005, Neely 1998).

Figure 1.19: The Customer Innovation Center of GE Plastics houses thousands of samples of plastics

Since smaller material producers usually do not yet have the existing client base, the reputation or the in-house facilities that large material producers have (see for example the Customer Innovation Centre of GE Plastics in figure 1.19) to directly convince large application manufacturers (which usually combine the design, processing and application manufacturing nodes, see figure 1.16), they will usually first need to convince other nodes in the value chain to even consider the implementation of the new material. Due to their strategic position in the value chain (between the material producer and application manufacturer) and their ability to translate a new material in an application with potential in appropriate high end markets, designers may therefore act as material champions, especially for small material producers (Bas 2007, van Bezooyen 2007). These designers may either be independent or be imbedded in the design department of small to medium sized application manufacturers, since small material producers are usually not able to meet material quantity demands of large application manufacturers. However, as can be seen in figure 1.17, the designer also comes early in the chain and is

[25] Please note that there is no generally accepted definition for Small and Medium sized Enterprises (SMEs); some definitions are based on quantitative standards (e.g. employee number or capital value), and others on qualitative aspects (e.g. management style, method of operation). In this thesis the definition of the World Bank is adopted (Ayyagari et al. 2003): Small and medium enterprises refer to companies with up to 300 employees.

dependent on many other nodes downstream (e.g. processors, outlets, etc.) which need to be convinced before the product in which the new material is used may actually reach the final consumer market.

Designers may also be able to play a role in stimulating the commercialization rate of bamboo in consumer durables in Western Europe for two reasons. First of all, in subsection 1.2.3 it was already found that designers directly influence various obstacles found in the bamboo PCS (i.e. product design capacity, lack of knowledge and lack of value chain networks) influencing the eventual commercialization rate of the material. Secondly, due to the immaturity of the bamboo sector all bamboo material suppliers in the North belong to the SME sector for which, as seen above, the involvement of designers seems a suitable strategy to stimulate the commercialization rate. Below is substantiated which consumer durable market may be suitable to target through the involvement of designers for bamboo suppliers in Western Europe.

1.3.2 Enabler Market for Bamboo

Market Selection as Strategic Tool in New Material Commercialization

According to Musso (2005) the tiresome commercialization process of new materials (see table 1.7) may be accelerated by strategic market selection. In his PhD thesis Musso argues, based on a historic analysis of the commercialization of plastics in the USA, that choosing right initial markets for new materials may be crucial to accelerate the commercialization process. Although material producers tend to directly try to substitute incumbent materials in mass markets, Musso explains that before a new material can actually compete with established materials, first, an understanding needs to be created about the material throughout the value chain nodes. If new materials target mass markets before this understanding is created, the intensity of the obstacles mentioned in subsection 1.2.3 will most likely be higher, and will lead to higher costs and delays in the commercialization process (see for example the case of the premature introduction of Polystyrene in children's toys in appendix B). Musso argues that first understanding should be created about the new material in a value chain through "enabler applications".

In short, enabler applications in general have a *simple value chain* with a relatively *high fault tolerance* in *small markets* with a *high visibility* and a *low material - cost sensitivity*, providing *credibility* of the *unique value* of the material, while developing *knowledge* and *capability* along the value chain nodes.

After the material has proven its worth in the enabler application, it can be launched in "platform applications". Musso (2005) defines a platform application as "the first large-market application in which a material is so compelling that all application manufacturers must use it in order to be competitive, thereby creating a path for future growth of the material in other major markets." In the platform application a material can really show its value based on superior properties over incumbent materials (usually not lower cost). More importantly, the platform application serves as a spring board to other large adjacent markets in the "widespread adoption" phase. Usually platform markets are markets that value high performance, are material-cost insensitive, and can accept a degree of risk. Note that the degree of risk strongly depends on the cost of failure, which will differ per industry (e.g. unacceptable in nuclear industry). New materials are therefore mostly adopted in platform applications in material cost insensitive industries such as high end appliances, furniture, automotive, sports equipment, aerospace and biomedical equipment (Ashby and Johnson 2002).

Once sufficient knowledge has been developed over the value chain, the switching costs caused by obstacles during the commercialization of new materials are overcome and the material has shown its value in enabler- and platform applications, the new material can compete with established materials on costs and performance in the widespread adoption phase. In this phase "battles" between materials can be fierce, with many different materials targeting various market segments simultaneously (Musso 2005). Musso's study shows that the few plastics which followed the strategic enabler-platform market selection path were quicker in successfully reaching the widespread adoption phase than most material producers who directly tried to target mass markets.

Interior Decoration as Enabler Market for Bamboo

In subsection 1.2.1 it was substantiated that for bamboo it would be suitable to target markets where (hard)wood is the incumbent material. Looking at current consumption of wood in the Netherlands, one can see that wood is mostly consumed in the building industry followed by the garden sector, DIY sector, pallet industry, furniture industry and in civil engineering projects (see figure 1.20). Although in general hardwood consumption is a lot smaller than softwood consumption in Western countries (see figure 1.21 for the Netherlands as an example), the volumes are still very high, especially compared to current bamboo consumption figures.

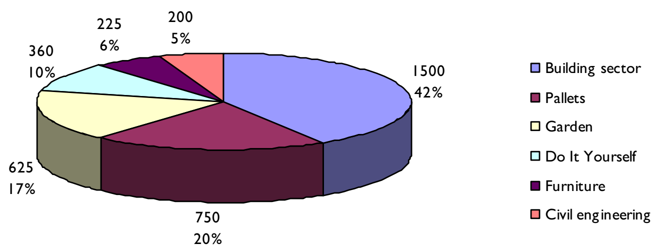

Figure 1.20: Consumption of processed wood in the Netherlands in 2001 per sector, 1000 m3 (Kuiper and Jans 2001)

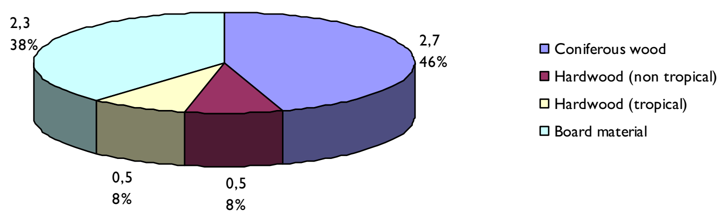

Figure 1.21: Consumption of wood in the Netherlands in 2004, million m3 (adapted from (CBS 2006)

Taking the market selection strategy developed by Musso (see above) as the point of departure, what could be a suitable enabler market for bamboo, before mass markets such as the building industry should be targeted? It should be noted that the market selection strategy developed by Musso is based on experiences with the commercialization of plastics, which was - when launched in the middle of the 20th century - a completely new material with a completely different chemical composition and properties compared to established materials. Therefore, for plastics it was easy to find an enabler application in which the unique properties of the material could be used. For bamboo in its raw form (stem) but especially in the various semi finished materials, the situation is different. The chemical composition of bamboo and wood, the incumbent material it tries to replace, is very similar; especially industrial processed bamboo resembles wood in various properties (technological, economical, and sensorial properties). Therefore, for bamboo it is more difficult to find a unique enabling application to pave the way, because unique selling points based on hard technical and economical aspects are difficult to locate compared to (hard)wood. However, softer aspects related to product experiences and emotions are becoming more important, and in this realm bamboo can also search for unique features to distinguish itself. Taking this into account potential initial target markets for bamboo were explored, based on the various enabler criteria. As a result, the *medium to high end interior decoration market*, used to categorize the combined markets of interior design, furniture and accessories, was chosen as the best initial market for bamboo to introduce itself. The choice for this particular market is explained below.

Because the bamboo industry is still relatively small (and therefore lacks economies of scale advantages) and materials have to be brought in from overseas, most bamboo materials (except the bamboo stem) cannot compete in price with most softwood and wood based board materials. Prices for most industrial bamboo materials are on a similar level as most hardwood. Therefore, especially for industrial bamboo materials it makes sense to focus on high end markets which are less material - cost sensitive, in which both the harder properties (e.g. relative hardness) and softer aspects of bamboo materials are appreciated. The high end interior decoration market is a typical material-cost insensitive market in which softer aspects are also important. In the interior decoration market bamboo can distinguish itself through softer aspects such as aesthetics and its perceived environmental sustainability, which might prove to be the strongest unique selling point for bamboo.

Furthermore, in the case of new materials - which especially industrial bamboo materials are - the identity of the material can still be "molded" based on first associations (van Bezooyen 2007). As is further explained in appendix D, if a material and its application grow up together, they are attached to each other. If the material is first introduced in a hip product, it will be associated with the characteristics of the product (see various examples in appendix D, e.g. the use of neoprene in sports equipment). Evidently, associations with high end interior decoration products will have a positive influence on the image of bamboo as a material.

Additionally, most value chains of products in the interior decoration market are relatively simple (compared, for example, with the value chains of domestic appliances), in which the same machines as deployed for wood can be used, thus avoiding high costs related to switching machines and production processes.

Likewise, most products in the interior decoration sector are relatively fault tolerant (e.g. a small deficiency in a table has a smaller impact than a small deficiency in consumer electronics). More importantly, the active involvement of designers, which is topic of research in this thesis, is only valuable in markets where designers play an active role in the development of the product features. Designers play a very important role in the medium to high end interior decoration market. Furthermore, high end interior decoration is a highly visible market, and is a very good market to show what a material can do. For example, high end design chairs have been used by many designers in the past as a useful enabler application for new materials, to show the world the technical and aesthetic performance of a new material (e.g. glass fiber composites used by Charles Eames).

Finally, it is important to select an initial enabler/platform market which has many large adjacent markets with similar characteristics, to facilitate diffusion from one sector to another, which will not happen if the sectors are too different from each other (e.g. aerospace vs. domestic appliances). The high end interior decoration market, because it is a relatively large market, combines characteristics of both enabler and platform markets, and has many attractive adjacent markets attached to it with similar characteristics. Once bamboo has proven itself in the interior decoration market, a following promising platform market to target in the West could be the medium to high end segments of the building industry (e.g. in visible building elements in architecture). Since many architects first experiment with a material in furniture, this seems a logical sequence. In architecture the role of materials to give identity to the product (in this case the building) through its intangible properties might be even more important than in consumer products (van Bezooyen 2007). However, in the building industry the fault tolerance is lower, and conservatism of some stakeholders is higher (contractors), making it important for bamboo to first prove its value in the interior decoration sector. Once bamboo has proven itself in these sectors, other mass markets in which wood is the dominant material should be attacked, which applies mostly to the building industry as a whole (including the bulk low end segments). In subsection 9.3.3 further suggestions are provided for mass markets in which the various bamboo materials can serve as an alternative to incumbent materials in the future.

1.3.3 Main Research Question

It was previously substantiated that designers could possibly contribute to stimulate the commercialization of bamboo in products in the interior decoration sector in Western Europe. To what extent this assumption is valid, and under which circumstances, is the topic of this action research which is tested by making a design intervention in practice and which can be translated in the *main question (MQ)* of this research:
To what extent can design interventions successfully stimulate the commercialization of bamboo in products in the interior decoration sector in Western Europe?

After the development and structure of the intervention is introduced in chapter 2, in chapter 3 the main question of this research will be translated into several detailed research questions.

1.4 Research Classification

Generally speaking, all existing kinds of research can be divided in theoretical research and practical research. According to Verschuren and Doorewaard (2001), theoretical or fundamental research focuses on solving problems in the general theory known about a phenomenon, while practical research focuses on solving a problem through an intervention in an existing practical situation. Of course combinations of the two also exist. This research can be perceived as being practical. Practical research usually focuses on solving one or more aspects of the intervention cycle, which is defined as "a defined series of process steps that is taken in solving practical problems" (Verschuren and Doorewaard 2001). The intervention cycle consists of the following steps: 1) problem description, 2) diagnosis, 3) design, 4) intervention, and 5) evaluation. For each step a specific research strategy with its own methods of data collection can be formulated (e.g. diagnostic research, evaluative research, etc). For reasons of feasibility, practical research usually focuses on contributing to only one step of the intervention cycle. However, some kinds of practical research do cover a bigger part of the intervention cycle, such as action research, which focuses on understanding and solving a practical problem, and starts with the description of the problem and from there on covers all phases of the intervention cycle through diagnosis, action (design & intervention) and evaluation (den Hartog and van Sluijs 1995).

This research can also be entitled action research, a research strategy which was first developed by Kurt Lewin in the 1940s (Lewin 1948, Nystrom and Starbuck 1983). Action research focuses on the implementation of an intervention in the real world in order to solve a problem in practice (e.g. in an organization), and includes the analysis of the execution of the intervention. Furthermore, contrary to traditional experiments, in action research the researcher and members of the organization in which the intervention takes place actively participate in the change process in order to bridge the gap between science and practice. Action research is problem driven, puts the client in center, questions the status quo, and results in empirical verifiable conclusions that can be used to eventually form theories that are also applicable in practical reality (Argyris 1983, den Hartog and van Sluijs 1995). Note that action research has a double meaning: it is both a research strategy and an intervention method. As a research

strategy strictly taken it can be considered a field experiment with a practical purpose, although compared to experimental research, in action research the role of the researcher is participatory.
The main advantage of action research is the high validity of the results through the problem oriented approach; because the intervention takes place in reality, actively involves participants throughout the process and continuously processes their inputs in a step-by-step manner, a high level of learning is created on the spot, custom-made for the situation (van der Zwaan 1995). Although this high validity a.o. through the active participatory involvement of the researcher is a strength of action research, it is also a weakness. Through the close involvement of the researcher as a change agent throughout the process, the researcher takes his own beliefs and values into the intervention, which could lead to biased results. This does not need to be a problem, as long as the researcher acknowledges this potential bias and is able to objectively describe his role during the process. Subsection 3.4.2 will explain how this was assured for this research. Another disadvantage of action research is the fact that the double role of the researcher as facilitator/organizer and researcher is very time consuming, and requires a lot of effort from the researcher to switch between roles throughout the process. For more background information about the main elements of action research the reader is referred to appendix F.
Since prior research on the development of design interventions to accelerate the commercialization rate for new materials including bamboo is scarce, this research has an exploratory character. In contrast with experimental research, in the evaluation of the intervention the execution process is also included since it is crucial to understand if and how the intervention works, and how the intervention can be improved for potential future interventions (van der Vall 1980). For evaluation of an implemented intervention this consists of a) measuring the intervention impact (product impact), b) monitoring of the intervention process (process evaluation), and c) the development of an advisory intervention which entails recommendations for both a) and b). Based on these various evaluation elements the various research questions 1-4 will be formulated in section 3.1.

1.5 Scope and Delimitations

The most important delimitations that determine the scope of this research are based on the main elements of the main question of this research (see subsection 1.3.3 above), which are further elaborated upon below.

Stakeholder Focus

Although there are many value chain nodes (see figure 1.16) that determine if a new material will actually be implemented in a product in the final consumer market, this thesis primarily focuses on the potential role of the *designer* (as one of these value chain nodes) to stimulate the commercialization process of bamboo. Although the primary focus of the intervention developed within this research is on the designer, some other value chain nodes downstream (closer to the consumer), such as the processor, application manufacturer, and retail outlets are integrated as secondary stakeholders in the intervention as well (for more information see subsection 2.2.1).

Regional Focus

Because of the increasing interest in sustainability in the West providing interesting potential growth markets, and the Western trend following character of emerging economies and developing countries, the focus of this research is on commercialization of bamboo in products in *Western Europe*, and in particular on the two countries in the EU which were the first to adopt and import industrial bamboo materials and still have a leading role with respect to industrial bamboo commercialization: the

Netherlands and Germany. At the moment Germany is clearly the largest industrial bamboo consumer in the EU; the German market alone accounts for more than 50% of the whole consumption of bamboo flooring and veneer in the EU (van der Lugt and Lobovikov 2008). When this research refers to "Western Europe," these two countries are meant.

Before bamboo is successfully commercialized in a consumer durable in Western Europe, it will go through various value chain nodes that have to overcome obstacles related to various activities (e.g. plantation, harvesting, processing, transport, etc.). Since giant bamboos suitable for industrial utilization grow in the South, obstacles during the PCS will relate to both stakeholders in the South and stakeholders in the North (Western Europe). However, the design intervention introduced in chapter 2 will take place at *the consumption side of the PCS, based on design and production of products in the North*, using bamboo materials from China, as the leading bamboo producer and exporter worldwide.

By choosing a particular PCS in which the obstacles in the South are already solved, only obstacles in the North will be tackled through the design intervention in this research. Note that despite the focus on the North, in various parts of this thesis results are also of direct interest for bamboo producers in the South, either because of the generic character of the results (e.g. material properties appreciated by designers; see section 6.2) or because of their potential interest to target Western export markets in the future.

Market Focus

The potential role of the designer to stimulate the commercialization rate was investigated for the use of bamboo for products in the *medium to high end interior decoration sector,* which is presumed to be a suitable enabler market for bamboo (see arguments for this choice in subsection 1.3.2).

Sustainability Focus

The choice for bamboo in this research is derived from the potential environmental virtues of bamboo, and therefore stems from the Planet component of the Triple Bottom Line. Consequently, this research focuses on the potential of bamboo as *environmentally sustainable* material in Western Europe. Obviously, this does not mean that bamboo does not have potential for the socio-economic components of sustainability. On the contrary, through its abundant availability in the South, usually in distant rural areas, bamboo has much potential to contribute to local socio economic growth and thus to sustainable development. Although it is not the focus of this research, some recommendations will be provided to take these socio economic benefits in future interventions into account as well (see subsection 9.3.2).

Resource and Material Focus

This thesis 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 document). 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 of the design intervention in this research apply in particular to this species and similar giant bamboo species apt for industrial utilization like *Guadua spp.* (referred to as "Guadua" in the remainder of this document) and *Dendrocalamus Asper*.

Figure 1.22: Guadua is a giant bamboo which grows in clumps mainly in Latin America which may reach heights up to 25 meters

As was shown above, there is a wide array of industrially and non-industrially produced bamboo materials available in the South. The focus in this thesis 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* and *mats* as representatives for non industrial bamboo materials, and *Plybamboo (board and veneer), Strand Woven Bamboo (SWB), Bamboo Mat Board (BMB) and bamboo composites* 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.

1.6 Thesis Structure

This thesis consists of three parts: an introduction (part I), the results (part II) and the conclusions & recommendations (part III).

Part I consists of the problem analysis leading to the main research question in chapter 1, the development of the design intervention in chapter 2 and the research design including the conceptual framework and the operationalization of the main research question in detailed research questions in chapter 3.

Part II of the research is structured based on the main elements of action research: the evaluation of a design intervention, after which advice for improvement should be provided (as input for a possible new intervention cycle). In chapters 4-7 the complete intervention is evaluated based on the various components as distinguished by van der Vall (1980), and therefore is divided into an evaluation of developed product prototypes during the intervention based on their market potential, innovative character (chapter 4) and their environmental sustainability (chapter 5), an evaluation of the bamboo materials deployed in the intervention (chapter 6), and an evaluation of the intervention itself based on relevant success indicators measured before and after the intervention as a kind of black box indication (chapter 7). In chapter 8 the process of the intervention is analyzed and evaluated: "what happened in the black box?" Based on the findings, suggestions to improve the intervention in the future are provided. Each chapter in part II more or less follows the structure: introduction (including methodology used) - results - conclusions.

In part III (chapter 9) conclusions are provided as well as policy recommendations for the bamboo industry and recommendations for further research. Chapter 9 also explores under what circumstances the design intervention for bamboo evaluated in this research could be replicable for other materials as well. The structure of this thesis, including the research questions (RQ) which will be further introduced in chapter 3, is represented in figure 1.23 below.

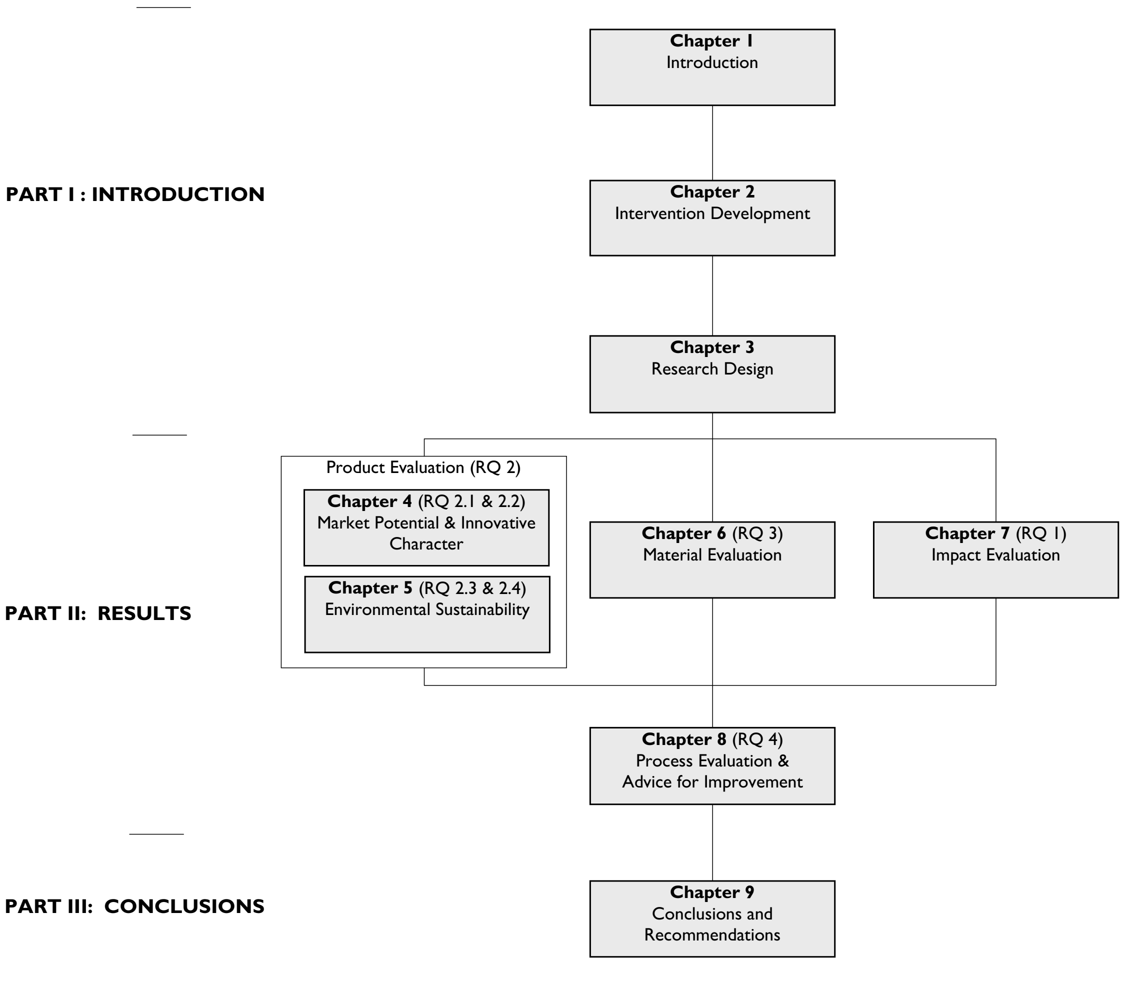

Figure 1.23: The outline of this thesis