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# Bamboo as a building material alternative for Western Europe? A study of the environmental performance, costs and bottlenecks of the use of bamboo (products) in Western Europe

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**Abstract**—For two bamboo products, bamboo in its natural form (the culm) and in an industrial form (as a panel), the environmental impact was determined and compared to alternatives. This comparison was made using a model that uses data from Life Cycle Assessment (LCA), based on the use of these products in the Netherlands. The consequences of the application of bamboo culm in the building process of 5 bamboo building projects in Western Europe were also analysed.

*Key words*: Bamboo; environmental performance; LCA (Life Cycle Assessment); costs; Western Europe; success factors; failure factors.

## INTRODUCTION

In the building industry, costs and durability are the main factors determining the selection of a building material. However, with sustainability as a key issue in the last decades, especially in Western countries, the environmental performance of building materials has become more important criterion. Bamboo, as a fast growing renewable material with a simple production process, is expected to be a sustainable alternative for more traditional materials like concrete, steel and timber. In many publications (e.g. Refs. [1–3]) bamboo is qualified as a very sustainable material. However, this has never been proven quantitatively. The building materials that are most commonly used in the Western world have already been assessed environmentally using tools based on Life Cycle Assessment (LCA) methodology.

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In the study presented, an LCA was conducted for bamboo, in its original form (the culm) and in an industrial product application (a wall panel). The different environmental effects resulting from LCA were converted to unified end-results by means of the TWIN$^{2002}$ model, which will be discussed below.

In Europe and the United States, bamboo is being used more often, either in its natural form (the culm) or as part of an industrial product (e.g. in panels, parquet). In Europe, some building projects were based on bamboo constructing. During these projects, specific problems encountered during the building process were a direct consequence of the use of bamboo. In order to assess the influence of bamboo during the building process, major factors of failure (and success) were analysed. In future bamboo projects, acknowledging these problems and analysing the causes will help prevent a negative impact on duration, money and quality.

## OUTLINE OF THE STUDY

### *Objectives*

The first objective of the study presented focuses on the product bamboo:

– Gaining more insight into the environmental performance of bamboo (products) compared to building materials more commonly used in Western Europe.

The second objective focuses on the application of the product bamboo in the building process:

– Gaining more insight into the critical factors of success and failure of the application of bamboo in building projects in Western Europe and finding solutions to prevent or reduce the negative consequences.

For these objectives, the following research questions needed to be answered:

– What is the environmental impact of bamboo (products) in Western Europe compared to building materials more commonly used?
– Considering bamboo building projects in Western Europe, what are the success and failure factors related to the use of bamboo, and how can the negative consequences be avoided or reduced?

### *Restrictions*

The following bamboo products were environmentally assessed:

– Air-dried culms of the bamboo species *Guadua angustifolia*, produced in the National Bamboo Project in Costa Rica, based on use (including transport) in the Netherlands. Initially, we also wanted to assess an Asian bamboo species, *Phyllostachus pubescens*. However, due to communication problems and lack of data this assessment could eventually not be executed.
– Bamboo panels (*Plyboo* natural plain-pressed two-layered bamboo panel), produced in Shanghai (China) for use in Holland, used as cover for inner walls.

*Research method*

Data of the production process of both the bamboo culm and panel were retrieved through interviews with experts and literature study. The data were processed in the $TWIN^{2002}$ model, an assessment tool developed, based on the LCA-methodology, by experts from the Dutch consultancy company NIBE Research.

Factors of success and failure were based on case studies and extracted from interviews with people involved in the building process. The interviews were analysed using qualitative research methodology.

## THE ENVIRONMENTAL ASSESSMENT

*Background*

In 1990, Speth [5], and Ehrlich and Ehrlich [6] argued that, in order to achieve sustainable development (i.e. development that provides in the needs of the current generations without threatening provision of the needs of future generations [4]) in the future, the pressure on the environment should be reduced by 20-fold. This target has been adopted by many organisations and societies. One of the ways to achieve a 20-fold environmental improvement in the building industry is using more sustainable and renewable materials.

*LCA*

Life Cycle Assessment (LCA) is the basis commonly acknowledged for environmental assessment of products. Principally, in an LCA, all environmental effects occurring during the life cycle of a (building) product are analysed, from the extraction of resources until the end phase of demolition or recycling (‘from cradle till grave’). The LCA methodology developed by the Centre of Environmental Studies (CML, in Leiden, the Netherlands) was presented in 1992 [7]. It was internationally standardised in the ISO 14040 series [8–11].

A standard LCA includes quantifiable environmental effects; some effects (e.g. ‘deterioration of eco-systems’) are ignored until a generally accepted assessment method has been developed. Furthermore, the standard LCA provides an outcome of different effect scores; a weighing method is not included and an overall judgement of products is, therefore, not possible. In order to obtain a single score and enable comparison of products, additional models are necessary. At present, many of these models are available, each one having advantages and disadvantages. The validity of the models is always subject to discussion, mainly about the applied weighing method [12].

*The $TWIN^{2002}$ model*

For the environmental assessment of bamboo and its alternatives the $TWIN^{2002}$ model was chosen, an improvement of the TWIN model developed by Haas [13] and the basis for many building products' assessments in the Netherlands. The assessment process in the TWIN model follows the methodology of LCA until aggregation and then adds a weighting step:

(1) Definition of the functional unit and process tree.

(2) Inventory of environmental interventions.

(3) Aggregation to environmental effect equivalents.

(4) Weighting to indices.

TWIN was based on the first CML LCA methodology, whereas TWIN$^{2002}$ largely follows CML2, the most recent version of the LCA methodology [14]. A significant difference between the original TWIN and TWIN$^{2002}$ model concerns the weighting: TWIN offered a weighting scale for the environmental effects, whereas TWIN$^{2002}$ does actually not weight; however, it adds a multiplication by environmental costs per effect (explained below), which, for an end-performance, can be summed.

*Environmental effects taken into account*

Table 1 provides an overview of the environmental effects included in the inventory of TWIN$^{2002}$. As can be seen in Table 1, for a great part TWIN$^{2002}$ applies environmental data of materials and products acquired in accordance with CML2. However, the model also includes other quantitative and estimative methods for environmental effects that a 'pure' LCA lacks.

*Environmental costs*

The environmental costs weighting methodology of TWIN$^{2002}$ is based on the principle of prevention costs [16] or eco-costs [17]: costs that are related to the prevention of environmental damage by certain interventions (e.g. emissions), but not included in real prices of products and eventually paid for by society, through general taxes. As monetary factors, these hidden environmental costs can be coupled to environmental effects acquired through LCA, resulting in a single score in (environmental) euros or dollars.

The advantage of the hidden environmental costs methodology is the absence of a subjective weighting; the complexity, however, is the exact determination of monetary factors. The monetary factors applied in TWIN$^{2002}$(see Table 2) were determined from various references (discussed in Ref. [18]).

*Functional unit of the comparison*

For the comparison of alternatives to a certain function, a general basis needs to be defined. This basis is called the 'functional unit' [9, 12]. For a correct comparison, the functional unit is of vital importance: measurements of the alternatives are determined by its technical and functional requirements (e.g. strength and stiffness).

**Table 1.**
Environmental effects inventarised in TWIN[2002], with their unit and determination method

| Environmental effect | Unit | Method |
|---|---|---|
| Emissions | | |
| Global warming | kg $CO_2$ eq. | CML2-baseline, $GWP_{100}$ |
| Ozone layer deterioration | kg CFC-11 eq. | CML2-baseline, ODP8 |
| Human toxicity | kg 1,4-DB eq. | CML2-baseline, HTP8, global |
| Aquatic toxicity | kg 1,4-DB eq. | CML2-baseline, FAETP8, global |
| Terrestrial toxicity | kg 1,4-DB eq. | CML2-baseline, TAETP8, global |
| Photo-chemical oxydant forming | kg $C_2H_4$ eq. | CML2-baseline, high $NO_x$ POCP |
| Acidification | kg $SO_2$ eq. | CML2-baseline, average European AP |
| Eutrification | kg $PO_4$ eq. | CML2-baseline, generic EP |
| Depletion | | |
| Biotic resources | ELM | TWIN |
| Abiotic resources | ELM | TWIN |
| Energy | ELM | TWIN |
| Land use | PDF* $m^2$/yr | Eco-indicator 99 |
| Nuisance | | |
| Stench | $m^3$ OTV | CML2-baseline, inverse OTV |
| Road transport noise | DALY | Müller-Wenk |
| Manufacturing process noise | ELM | TWIN |
| Light | ELM | TWIN |
| Calamities | ELM | TWIN |

Data from Ref. [15]. ELM = environmental load mark.

It means that weaker alternatives require more material, and that alternatives with a shorter life span need to be maintained or replaced more often (both leading to higher annual environmental costs).

In the study presented, bamboo was environmentally assessed in its natural form (culm) and in an industrial form (panel). The bamboo culm was assessed in the structural function as a column, transversal and longitudinal beam and rail, as applied in the walking bridge in the Amsterdamse Bos (Fig. 1), the dimension of each functional element defined by the original technical requirements, mainly strength and stiffness. The functional unit was 1 m of these functional elements, based on the original loads and lengths, applied in the bamboo bridge in the Amsterdamse Bos.

For the bridge, the functional elements of bamboo and their properties were compared to the same functional elements of building materials most commonly used in these applications: steel, sustainably produced timber (species: *azobé* and *robinia*) and concrete. Concrete was only considered in the functional element 'column', because it is not commonly used as a line element in bridges.

In the actual bridge, the longitudinal beam is constructed of steel. For the assessment of bamboo, for the same strength, this steel member was theoretically replaced with four bamboo culms, an unfavourable solution because in practise,

**Table 2.**
Environmental costs per environmental effect applied in TWIN[2002]

| Environmental effect | Environmental costs | |
|---|---|---|
| Emissions | | |
| Global warming | 0.091 | €/kg $CO_2$ eq. |
| Ozone layer deterioration | 5.725 | $10^3$ €/kg CFC-11 eq. |
| Human toxicity | 0.048 | €/kg 1,4-DB eq. |
| Aquatic toxicity | 0.048 | €/kg 1,4-DB eq. |
| Terrestrial toxicity | 0.048 | €/kg 1,4-DB eq. |
| Photo-chemical oxydant forming | 4.402 | €/kg $C_2H_4$ eq. |
| Acidification | 2.723 | €/kg $SO_2$ eq. |
| Eutrofication | 54.454 | €/kg $PO_4$ eq. |
| Depletion | | |
| Biotic resources | 0.042 | €/ELM |
| Abiotic resources | 0.042 | €/ELM |
| Energy | 0.042 | €/ELM |
| Land use | 0.205 | PDF* $m^2$/yr |
| Nuisance | | |
| Stench | 0.233 | $10^{-7}$ $m^3$ OTV |
| Road transport noise | 3.219 | $10^2$ DALY |
| Manufacturing process noise | 0.149 | $10^{-6}$ €/ELM |
| Light | 0.024 | €/ELM |
| Calamities | 0.024 | €/ELM |

Data from Ref. [15].

**Figure 1.** Bamboo bridge in the Amsterdamse Bos (photo by Pablo van der Lugt).

a compound beam would more probably have been designed instead, requiring less bamboo material.

Table 3 presents the properties of the alternatives in their respective application. The lifespans were determined in consultation of experts (J. Janssen, personal com-

**Table 3.**
Properties of the alternatives for different functional elements of a bridge

| Functional element | Type | Measurements | Lifespan (years) |
|---|---|---|---|
| Transversal beam | | | |
| Timber | Azobé | 100 × 200 mm | 25 |
| Timber | Robinia | 120 × 225 mm | 15 |
| Steel | IPE 100 | IPE 100 | 50 |
| Bamboo | Guadua | 1 culm, average diameter 100 mm | 20 |
| Column | | | |
| Timber | Azobé | 120 × 120 mm | 25 |
| Timber | Robinia | 140 × 140 mm | 15 |
| Steel | tube | 120 × 120 × 3 mm | 50 |
| Concrete | prefab element | 150 × 150 mm | 50 |
| Bamboo | Guadua | 1 culm, average diameter 100 mm | 20 |
| Rail | | | |
| Timber | Azobé | 100 × 100 mm | 25 |
| Timber | Robinia | 100 × 100 mm | 15 |
| Steel | tube | 80 × 80 × 3 mm | 50 |
| Bamboo | Guadua | 1 culm, average diameter 100 mm | 20 |
| Longitudinal beam | | | |
| Timber | Azobé | 100 × 230 mm | 25 |
| Timber | Robinia | 100 × 260 mm | 15 |
| Steel | HE-A 140 | HE-A 140 | 50 |
| Bamboo | Guadua | 4 culms, average diameter 100 mm | 20 |

munication; P de Blaey, personal communication; W. Nijland; personal communication; J. Haasnoot, personal communication).

### *Environmental data and assumptions used for bamboo*

All steps in the production process and life span of the bamboo culm needed to be analysed. The data were retrieved through enquiries (J. Janssen, personal communication; W. Garcia, personal communication; B. Erickson, personal communication; G. Gonzalez, personal communication). Tables 4–9 present the data acquired.

### *Assessment of the bamboo culm*

After processing these data in the $TWIN^{2002}$ model, the environmental costs of 1 kg bamboo culm over the production process could be analysed (see Fig. 2, an adaptation of the original output). The results are given in micro-points (mPt), equal to $10^{-3}$ environmental euros ($e^{€}$). Figure 2 shows that almost all environmental costs originate from the (sea) transport from Costa Rica to the Netherlands.

In order to obtain the annual environmental costs, the environmental costs of each alternative (bamboo, timber, steel and concrete) were divided by the lifespan, as

**Table 4.**
Basic features of the bamboo species *Guadua angustifolia* from the production site at Guapiles, Costa Rica

| | |
|---|---|
| Density | 600 kg/m$^3$ (dry); 1.5 kg/m$^1$ |
| Length | up to 20 m |
| Diameter | on the ground: 10–15 cm, average: 10 cm |
| Thickness | 9 mm (average) |

**Table 5.**
Fertilizers/herbicides used per hectare in the production of the bamboo species *Guadua angustifolia* from the production site at Guapiles, Costa Rica

| Fertilizer/herbicide | Year of plantation | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| 10-30-10 (N-P-K) | 2 sacks | | | | | |
| Nitrate | 2 sacks | 2 sacks | 2 sacks | | | |
| Boron (Solubor or Menoral8) | | 3 sacks | 4 sacks | 8 sacks | 8 sacks | etc. |
| Herbicida (Glifisato) | 2 liter | | | | | |

1 sack equals 45 kg.

**Table 6.**
Energy consumption of the bamboo species *Guadua angustifolia* from the production site at Guapiles, Costa Rica

| Activity | Machines needed | Power | Fuel | Typical consumption |
|---|---|---|---|---|
| Sawing culms | chainsaw | | gasoline | 1 gallon/day: 234 culms of 10 m = 3510 kg bamboo (dry) |
| Branch removal | chopping knives | | | |
| Quality control | no machines used | | | |
| Preservation | air-pump | 1 kW | electricity | 160 kWh per installation for 160 culms = 2400 kg (dry) |
| Drying | no machines: open air | | | |

presented in Table 3. For other aspects, e.g. the amount of waste, recycling of the material also needed to be taken into account. Figure 3 presents the results including these aspects. Note that the numbers are not absolute environmental costs; however, they represent an index. For the index, the environmental costs of an alternative were divided by the environmental costs of the alternative with the lowest environmental impact (in all cases bamboo) and multiplied by 100. In case of a higher index, the environmental costs are greater and, therefore, the performance is worse.

Figure 3 demonstrates that the bamboo culm, even when used in Western Europe, can be considered the most sustainable alternative by far in all functions. In

**Table 7.**
Materials added during the productions process of the bamboo species *Guadua angustifolia* from the production site at Guapiles, Costa Rica

| Activity | Material description | Amount | Recycling | Consumption |
|---|---|---|---|---|
| Sawing culms | | | | |
| Branch removal | | | | |
| Quality control | | | | |
| Preservation | Timbor: $Na_2B_8O_{13} \cdot 4H_2O$ with 66% active boron ($B_2O_3$) | 100 liter water with 12% boron per 480 m culm = 720 kg (dry) | nearly 100%: in the culm or re-used as fertilizer | water: 100 l/day per 480 m culm = 720 kg (dry) |
| Drying | | | | |

**Table 8.**
Biomass remaining from the bamboo species *Guadua angustifolia* from the production site at Guapiles, Costa Rica

| | Total | Culm | Branches and foliage |
|---|---|---|---|
| Green mass (ton/ha) | 119 | 82 | 37 |
| Dry mass (ton/ha) | 72 | 53 | 19 |
| Sawing loss | | 10%[a] | |
| Mass remaining (ton/ha) | | 48 | |

Due to limited data, green and dry mass data are from the species *Gigantochloa scortechnii* [19].
[a] Of which 100% was re-used as compost at the plantation (W. Garcia, personal communication; B. Erickson, personal communication; G. Gonzalez, personal communication).

**Table 9.**
Transport of the bamboo species *Guadua angustifolia* from the production site at Guapiles, Costa Rica

| Route | Vehicle | Fuel type | Distance |
|---|---|---|---|
| Plantation–preservation/drying | Hyundai truck 4.5 ton | diesel | 2 km |
| Drying–harbour | Hyundia truck 4.5 ton | diesel | Guapiles–Limon: 80 km |
| Harbour–The Netherlands | Sea vessel[a] | diesel | Limon–Rotterdam: 10 000 km |

[a] Total energy consumption = 0.37 kJ/kg per km [20], based on an average sea cargo ship (engine power more than 4000 kW), with an empty weight of 5000–6000 ton and 14 500 ton cargo, including 12% of direct fuel consumption for capital goods.

some applications the earlier mentioned 20-fold 'environmental improvement' is achieved. The difference in environmental performance of the longitudinal beam and the transversal beam is due to the fact that four bamboo beams instead of one are needed for the longitudinal beam. Note that the assessed timber species are produced sustainably; timber from regular, non-sustainable forests will have an environmental impact that is considerably worse. The good environmental performance of the bamboo culm has two distinct causes. First, its natural hollow design is structurally far more efficient than a rectangular massive section, e.g. in the case of timber [19]. This means that bamboo contains far less material mass in a certain function compared to steel, concrete and timber. The second cause is the simple, short production process (sawing, removal of foliage, preservation, drying).

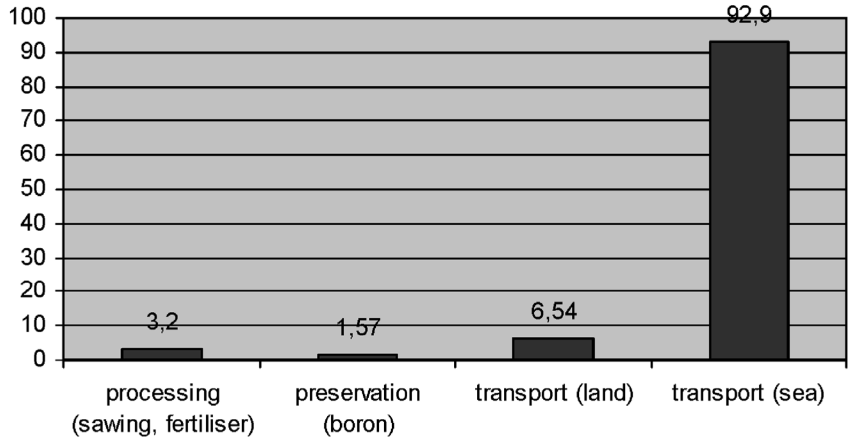


**Figure 2.** Environmental costs (in mPt) of 1 kg bamboo culm including transport to the Netherlands per part of the production process.

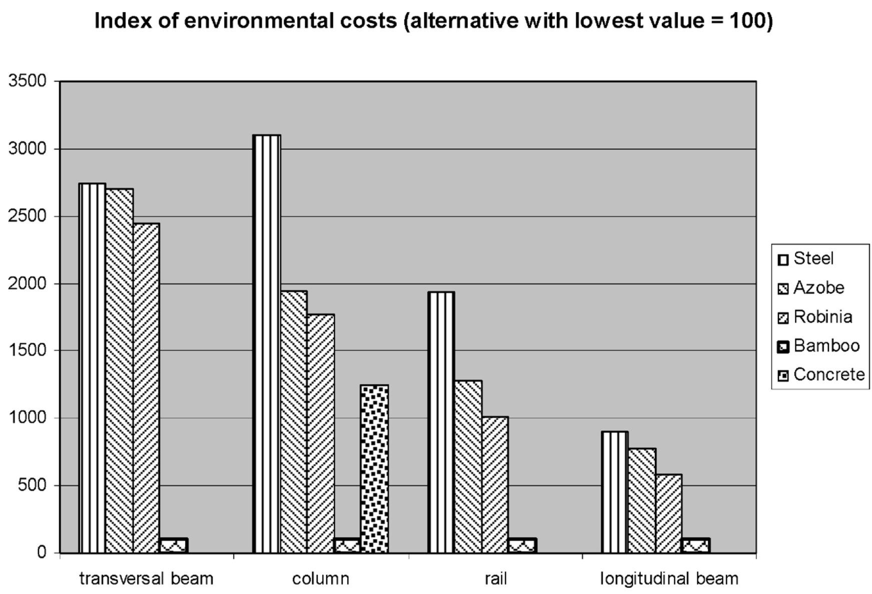


**Figure 3.** Index of the annual environmental costs of the different elements of the bamboo bridge in the Amsterdamse Bos.

Note that the assessed bamboo culm is dried in the open air without the use of a drying chamber (which would cost relatively more energy).

*Environmental assessment of the bamboo panel*

As an industrial product example, a bamboo panel was also assessed by environmental criteria, according to the methodology previously discussed. Bamboo panels are mainly used as parquet but can also be used in other applications, like veneer or covering material. In the study presented the panel was compared with wood-based panels. The functional unit was 1 $m^2$ of non-bearing internal wall covering.

Just as for the bamboo culm, the complete production process with corresponding environmental effects was analysed for the bamboo panel. However, the production process of the panel is far more complex. The bamboo culm needs to be sawn, smoothed, bleached, sandpapered, glued, pressed, etc. in order to obtain the characteristics required. Therefore, the environmental costs of 1 kg of bamboo panel are considerably higher than those of the culm. Figure 4 shows that the bleaching and preserving process by means of $H_2O_2$ has a great share in the environmental impact of this product. Again, (sea) transport has a great share in the total environmental impact of this bamboo product.

If other life cycle aspects, e.g. the life span and waste, are added, the bamboo panel can be compared with other materials (see Fig. 5). In this figure a theoretical version is also added in which the panel is not bleached but only preserved with boron, using the *Boucherie method* [19–21].

Figure 5 indicates that the environmental performance of the bamboo panel is slightly less favourable than most wood-based panels for non-bearing internal walls. However, the theoretical non-bleached version of the bamboo panel scores significantly higher. Only panels with wooden material originating from sustainably

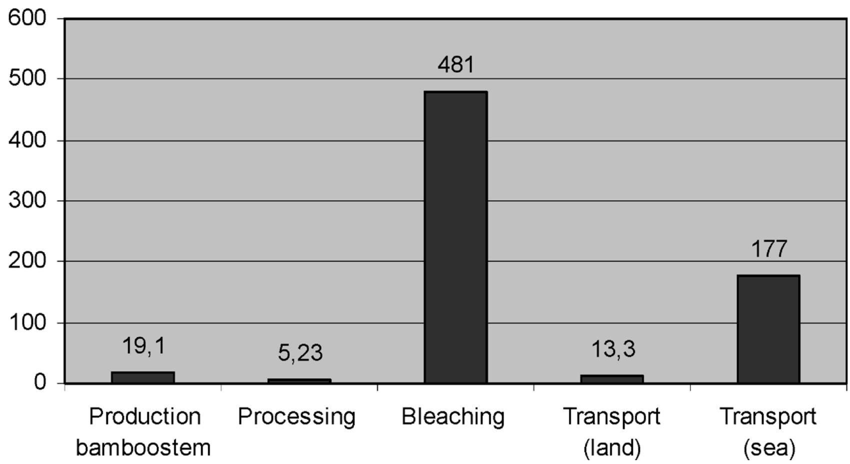


**Figure 4.** Environmental costs (in mPt) of 1 kg bamboo panel per part of the production process, including transport from China to the Netherlands.

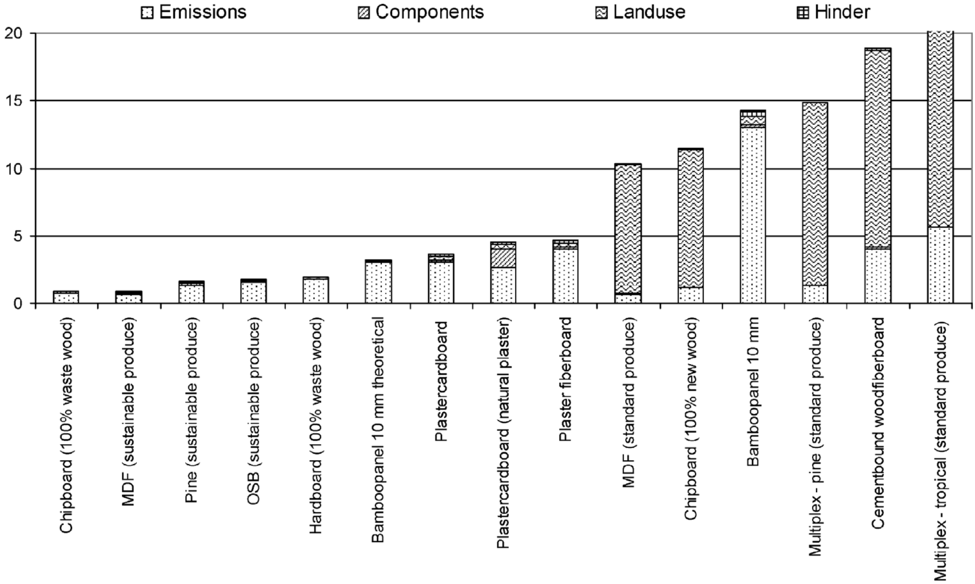


**Figure 5.** Environmental costs in euros per functional unit (1 $m^2$) of wood-based panels for internal walls including the bamboo panel.

maintained forests or panels made from 100% waste environmentally perform better than the theoretical bamboo panel. Concerning the limited availability of these products, the theoretical bamboo panel can be defined as a relatively sustainable alternative. As a result of the outcome of the environmental assessment of their product, the manufacturer of the bamboo panel, Plyboo Flooring International, is analysing the production process to see if it can be adjusted to get a more sustainable product. This shows the possibilities of LCA as a stimulus to improve the production process in order to acquire a more sustainable product. Note that panels based on metal and synthetic material were not included in Fig. 5. The environmental costs of these alternatives are expected to be higher than those of wood- and bamboo-based panels.

Nevertheless, especially when compared to the relatively sustainable bamboo culm, the bleached bamboo panel cannot be considered a sustainable alternative. This is due to the disposal of features that made the bamboo culm a sustainable alternative: the efficient structural natural design of the culm is deteriorated through the laminating process. The intersection becomes solid, meaning more material mass is needed to fulfil the required function. Furthermore, the process to make a rectangular massive product of the bamboo culm is far more energy-intensive and complex, leading to considerably higher environmental costs.

*Conclusions on the environmental assessment*

The environmental assessment of the bamboo culm yielded very positive results. In several functions the environmental performance of the culm is 20-times better

**Table 10.**
Annual production of plantations for producing timber and bamboo

| | Annual production (ton/ha) | | | |
|---|---|---|---|---|
| | Green (total) | Dry (total) | Green (culm only) | Dry (culm only) |
| Bamboo | 78.3 | 47.4 | 55.7 | 36.0 |
| Timber | 17.5 | 13.5 | 14.0 | 10.8 |
| Ratio B/T | 4.5 | 3.5 | 4.0 | 3.3 |

than building materials more commonly used, e.g. steel, wood and concrete. When laminating the bamboo culm for flat-shaped applications, i.e. panels, the environmental advantage is diminished.

These results form a dilemma: a problem with the application of the bamboo culm in Western countries is the irregular, hollow, round form, leading to problems in joints. By laminating, a rectangular section can be created, making joining easier. However, from an environmental point of view, the bamboo culm should be chosen, accepting possible problems of its geometry during implementation in the building process. These problems were analysed in the second part of the study, presented below.

### *Nuances*

Uncertainties are attached to environmental assessments, as by means of LCA. The reliability of some of the data available is also debatable. In order to compensate for this, the environmental assessment of bamboo took place following a worst-case scenario. Moreover, some environmental aspects that could be favourable to bamboo, like the annual production of biomass of a bamboo plantation (which is 3-times higher than for the average timber productive forest, see Table 10), were not included in the assessment.

Furthermore, the environmental assessment was based on the use of bamboo (products) in the Netherlands. When used in the country that produces the bamboo (in this case Costa Rica), the environmental costs of bamboo will be considerably lower, since there will be no sea transport here.

## CRITICAL FACTORS OF SUCCESS AND FAILURE OF BUILDING WITH BAMBOO IN THE WEST

### *Definition*

In terms of this research, a success or failure factor is defined as a negative (failure) or positive influence (success) on the costs, building time or quality of a building project, caused by the use of bamboo, compared to building materials more commonly used in Western Europe (e.g. timber, steel).

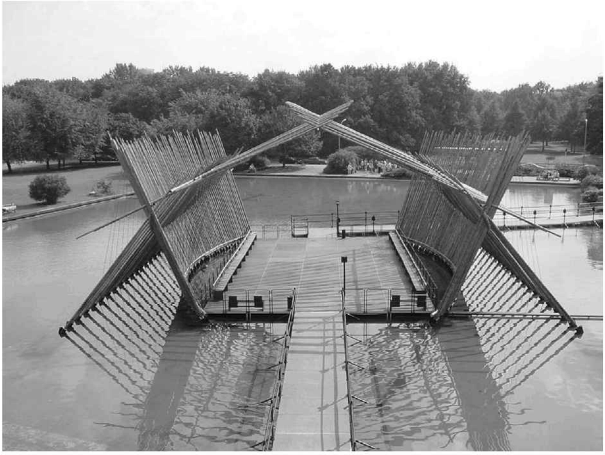

**Figure 6.** Bamboo theatre during the Festival of Vision, Berlin, 2000 (photo: Norbert Stück).

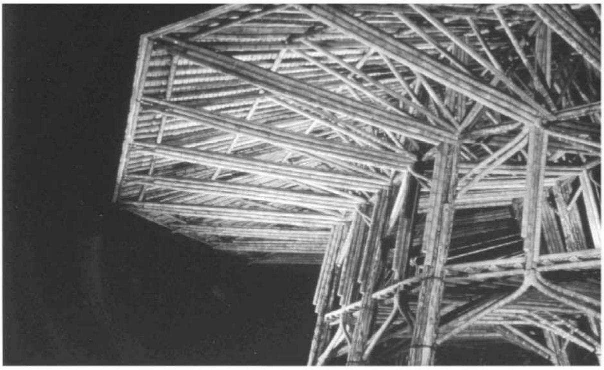

**Figure 7.** ZERI-pavilion during EXPO 2000, Hanover (photo by Louis Camargo).

In order to retrieve these factors, the largest bamboo building projects in Western Europe were analysed: the pavilion Bamboo summit city in Rotterdam 2002; the open-air theatre during the Festival of Vision, Berlin, 2000 (see Fig. 6); the ZERI-pavilion during EXPO 2000, Hanover (see Fig. 7); the walking bridge in the Amsterdamse Bos, 1999, and the bamboo tower at the Phenomena exposition Rotterdam, 1985, and Zurich, 1984.

*Critical moments*

As a result of the interviews held with 10 people involved in the building process of the projects, mainly failure factors and only few success factors turned out to have occurred. The analysis shows that there are a couple of moments during the building process that have a significant impact on the success of a bamboo project in Western countries (only the factors of success and failure occurring in most of the studied projects are given):

(1) The choice for a particular building method. The choice of a particular building method causes failure factors that occur in most projects: the deployment of workers from abroad (more expenses, communication problems), a larger and multi-lingual building organisation (leading to more miscommunication and delays) and more labour needed in making the joints. A factor of success is the ease to dismantle a bamboo structure.

(2) Purchase of the bamboo. This leads to failure factors like an intensive quality control, extra time for material preservation, and extra time and money losses due to bamboo import. On the other hand, the purchasing price of bamboo is relatively low (success factor).

(3) Testing the bearing capacity. In all cases extra tests and calculations, costing time and money, had been made to test the bearing capacity of the bamboo (structure).

(4) Acquiring a building permit. Beside the extra mechanical tests done on the bamboo in order to obtain a building permit, other tests were also required, e.g. on the 'fire safety' of bamboo. An unexpected success factor was the goodwill and cooperation of the involved authorities because of the fascination for this new building material.

A lot of other factors of success and failure cannot be clustered to a particular moment in the building process. These are failure factors like the cracks and moss forming on the material in the European climate, and the slipperiness of wet bamboo. Other success factors are the small amount of equipment needed, the low weight of the culms and the sustainability of the material.

*Main causes*

In order to avoid loss of time, money and quality in future bamboo projects, it is important to take the causes of the factors of failure into account before seeking solutions. All problems during the projects originate from 3 main causes related to bamboo:

(1) The shape of the material (round, hollow and tapered).

(2) Irregularity of the material.

(3) Lack of knowledge and building codes for bamboo.

Only laminating the bamboo (decreasing the environmental performance) or using a rectangular mould during the growth of bamboo (expensive) can avoid the first cause of many problems (the shape). Good plantation control and management, straightening the culms through heat treatment and a good quality control (J. Janssen, personal communication) can diminish disadvantages of the second main cause. Because problems related to both causes are inherent to the natural appearance of bamboo, they can only be diminished, not completely avoided. In spite of this, recommendations can be made to avoid loss of time, money, and quality in future bamboo projects. Some of the most important recommendations in the study presented concern the use of a simple structural design and accompanying building method (preferably not lashing), which can be executed by western workers, pre-manufacturing as many elements as possible, preserving by the Boucherie method and having a extensive quality control before purchasing the bamboo.

The third main cause of the factors of failure, the lack of knowledge and building codes for bamboo, has been diminished since the establishment of INBAR in 1997 and can hopefully be completely avoided in the future. INBAR is developing several international building codes for bamboo. These codes (DIS 22156 and 22157/1) have been submitted to the ISO (International Standards Organisation) and will hopefully be acknowledged in 2004 (J. Janssen, personal communication). Nevertheless, a lot of work still needs to be done. For instance, classification systems (already available for timber) still need to be developed for bamboo, for the raw material (classifications for quality and strength) as well as for complete joints. These can also be expected in several years (J. Janssen, personal communication).

### *Conclusions on the factors of success and failure*

Current developments, together with fulfilment of the recommendations made in the study presented, can avoid problems in future Western European bamboo projects that occurred in the past, leading to savings in time and money while adding quality.

For one of the projects, the walking bridge in the Amsterdamse Bos, a cost comparison was done, in which avoidable future incidental costs were not included. The cost comparison was done in accordance with the environmental assessment of the same functions (column, beam, rail) and materials (see Fig. 8). The costs assessment will not be discussed elaborately; we therefore refer to Ref. [22].

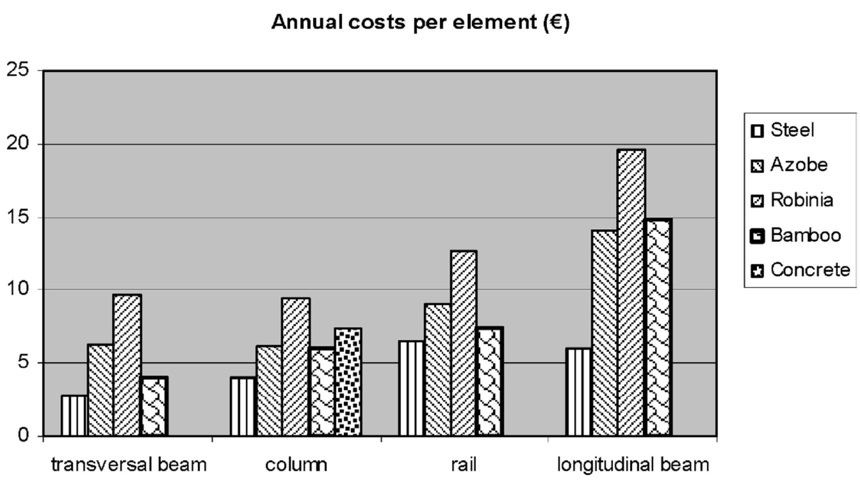


**Figure 8.** Annual costs of the various elements and materials of a bridge [23].

Figure 8 shows that the annual costs of bamboo can compete with the timber alternatives. Considering purchasing costs, bamboo is by far the least expensive. However, because of the shorter life span and the higher labour costs of assembling and disassembling, on an overall cost level, steel turns out to be the most favourable building material, due to the long life span.

## OVERALL CONCLUSIONS

The environmental performance of bamboo used in Western Europe highly depends on the form in which it is used. In its natural form (the culm), in several applications, bamboo proves more than 20 times as sustainable as the common western building materials timber, steel and concrete. When used as an industrial product (i.e. a wall panel) the environmental advantages of the bamboo culm are lost. Compared to most wood-based alternatives, the environmental performance of the assessed bamboo panel is slightly less favourable. Nevertheless, with some adjustments in the production process, a non-bleached sustainable alternative of the bamboo panel is possible. Furthermore, by applying a bamboo panel, technical problems related to the geometry of the culm can be avoided. Still, when choosing bamboo for its sustainability, it is recommended that the culm should be used.

Practical problems (failure factors) when using the bamboo culm in Western Europe are numerous and have a couple of bamboo-related main sources: the shape of the material, the irregularity of the material and the lack of knowledge and building codes. Many of these problems can be avoided in the future by following the recommendations done in this study. Furthermore, problems will be avoided through centralisation of knowledge and development of bamboo building codes by INBAR. Therefore, many problems in future bamboo projects in the West can be avoided, thus saving time and money while upgrading the quality of these projects.

The environmental and financial comparison demonstrates that bamboo can compete with building materials more commonly used in Western countries.

While many of the failure factors can be avoided in the future, some of them will remain. Bamboo is a natural product and will, therefore, always have some extent of irregularity. It is therefore suggested that in Western countries the bamboo culm should be used in functions were the measurement requirements are not entirely precise or fixed, as in temporary buildings (e.g. pavilions and tents) or small civil projects (e.g. bridges). Furthermore, bamboo can play a role as a finishing material (see Fig. 9).

## RECOMMENDATIONS FOR FURTHER RESEARCH

The environmental and financial comparison has been done for bamboo in a very specific application (column, beam and rail, as used in the walking bridge in the

**Figure 9.** Bamboo culm as a finishing material (photo by Hulshof architects).

Amsterdamse Bos). For a broader perspective of the environmental performance of bamboo (products), additional environmental assessments by LCA are needed:

- With data from more plantations, species and manufacturers, in order to increase the reliability of the results.
- Based on use in different countries (including the native country of the used bamboo).
- On another scale (complete joints, complete buildings).
- In other applications (using the bamboo culm internally, using the panel as parquet, using bamboo strips, etc.).
- In non-building applications (e.g. as biotic fuel).

For a broader perspective of the costs of bamboo (products) used as building material in the West, additional cost comparisons are needed:

- Of joints with other building techniques (e.g. lashing, joints with concrete).
- In another application (using the bamboo culm internally results in a longer lifespan).
- In another product (e.g. bamboo strips, corrugated board).

For a broader perspective of the failure and success factors of building with bamboo in the West, this research can be repeated in other Western countries (e.g. Canada, USA).

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