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An environmental, economic and practical assessment of bamboo as a building material for supporting structures

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Abstract

This paper discusses the potential of bamboo as a building material for Western countries. In the study presented, bamboo culms were environmentally and financially assessed and compared to building materials more common in Western Europe, e.g., steel, concrete and timber. Furthermore, a case study was done of temporary European bamboo buildings, structures and bridges, in order to determine factors of success and failure of building with bamboo. This paper presents the results of these studies, which indicate that within certain boundary conditions and with consideration of the recommendations following the case study, bamboo is a very sustainable building material for Western countries and can be competitive to materials more commonly used.

Keywords: Bamboo; Life cycle analysis; Case study; Building material

1. Introduction

1.1. Sustainability as a selection criterion for building materials

Building materials are commonly selected through functional, technical and financial requirements. However, with sustainability as a key issue in the last decades, especially in western countries, the environmental load of building materials has also become a more important criterion. In the year 1990, Speth [1] and Ehrlich and Ehrlich [2] introduced their relationship of sustainability with the world population, average welfare rate and environmental impact of welfare commodities, demonstrating the need of achieving a factor 20 environmental improvement by the year 2040. Many organisations and institutions have adopted this target. The building industry, directly or indirectly causing a considerable part of the annual environmental damage, can take up the responsibility to contribute to sustainable development by finding more environmentally benign ways of construction and building. One of the directions for solutions is to be found in new material applications: recycling and reuse, sustainable production of products, or use of renewable resources. Dobbelsteen et al. [3] found that approximately 60% of the environmental load of building materials in Dutch governmental offices is caused by the supporting structure of buildings (see Fig. 1). This emphasises the importance of innovative solutions for supporting functions. Bamboo, as a fast growing renewable material with a simple production process, is expected to be a sustainable alternative for more traditional structural materials, such as concrete, steel and timber.

1.2. Characteristics and applications of bamboo

Bamboo is a collective name for different species of giant grasses. It is estimated that 60–90 generae of

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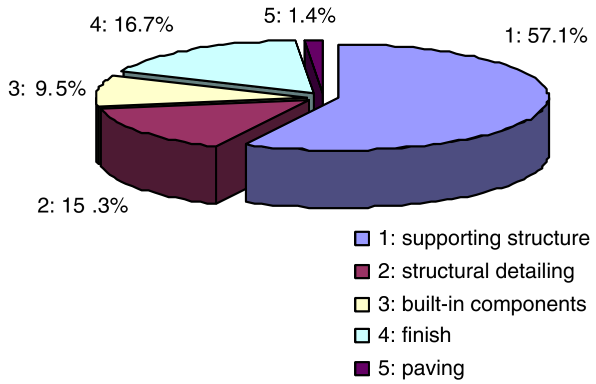

Fig. 1. Division of environmental load of building materials in office buildings [3].

bamboo exist, comprising approximately 1100–1500 species [4]. These species come in various sizes and forms (see Fig. 2). Bamboo mainly grows in tropical regions of Asia, Latin America and Africa.

Bamboo has a very efficient natural structural design; because of the hollowness and the fibers in longitudinal direction, less material mass is needed than in case of materials with a massive section, e.g., timber. In terms of load-bearing mass, as with all tubular elements, bamboo functions as an I-shaped cross-section, in each direction it is loaded, whereas other cross-sections are most efficient in one or two directions (see Fig. 3).

The efficiency of the natural design of bamboo is also demonstrated in Fig. 4, in which the strength and stiffness of various materials are divided by their mass per volume [6].

Fig. 2. Various species of bamboo [5].

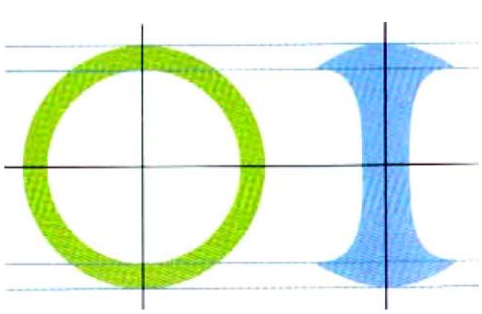

Fig. 3. Cross-section of bamboo [6].

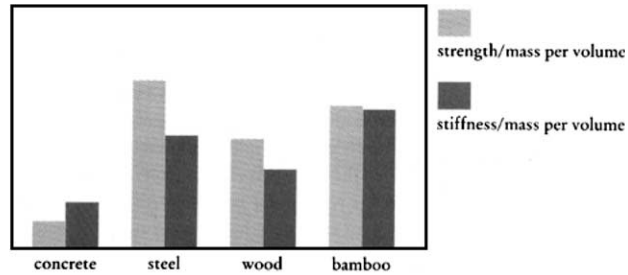

Fig. 4. Comparison of the stiffness and strength of various building materials divided by their mass per volume [6].

Due to the favourable mechanical properties, the high flexibility, the fast growing rate, the low weight and the low purchasing costs, bamboo is a building material with many opportunities. It can be used in many applications; from very traditional handicraft (e.g., baskets) to products that are completely industrialised (e.g., parquet and panels, see Fig. 5).

Some bamboo species can very well be used in supporting structures as the very high bamboo scaffolds against Eastern skyscrapers demonstrate (e.g., Fig. 6).

Bamboo is also used in the paper, food and evidently in the building industry. Especially for the less wealthy population in tropical areas, bamboo plays a very important role in daily lives (shelter, employment, income, fuel, etc.). Recently, bamboo has also found more applications in the West, in industrial applications as well as in temporary structures.

1.3. Studying the potential of bamboo for Western countries

1.3.1. Bamboo: a sustainable alternative?

Study was necessary to determine if bamboo can be considered sustainable. Some publications (e.g. [8–10])

Fig. 5. Various bamboo applications on the axis traditional–industrial [7].

Fig. 6. Bamboo scaffolding at the top of a new high-rise building in Hong Kong [photo: Andy van den Dobbelsteen].

already qualify bamboo as an environmentally benign material. However, until recently, this had never quantitively been proven. In contrast, the number of building materials assessed by environmental life cycle analysis (LCA) based methods is increasing fast. Therefore, the first research objective of the study presented [11] was to gain more insight in the environmental performance of bamboo (products) compared to building materials more commonly used in Western Europe.

In the study presented, an LCA based assessment was conducted for bamboo in its original form (the culm), comparing it to steel, timber and concrete alternatives in different structural functions. The reference project of the study was a bamboo bridge in the Amsterdam Woods, taking columns, transversal and longitudinal beams and rails as the structural elements for comparison.

1.3.2. Bamboo: an economic alternative?

The limited use of bamboo in Western Europe has provided little knowledge about the economic viability of bamboo as a building material. Therefore, the second research objective of the study presented [11] was to gain more insight into building and maintenance costs of the previously described bamboo applications, again compared to more common building materials, such as steel, timber and concrete. The reference was the same as with the environmental assessment, and the same structural elements were taken into account.

1.3.3. Bamboo case studies in Europe

In Europe, some building projects were executed with bamboo as the main structural material. During these projects, problems were encountered, some of which were direct consequences of the use of bamboo. This influence of working with bamboo needed to be analysed. Therefore, the third objective of the study presented was to gain more insight into critical factors of failure and success of the application of bamboo in Western European building projects, and to find solutions as to prevent or reduce the negative consequences of their causes.

2. Research methodology

2.1. Selection of studied bamboo products

The study presented was restricted to culms of the bamboo species *Guadua angustifolia*, produced during the National Bamboo Project in Costa Rica, air-dried there, and used in the Netherlands, thus including transport from Costa Rica to the Netherlands. Due to communication problems and lack of data, an Asian bamboo species, *Phyllostachus pubescens*, could not be assessed.

The assessment of an industrial product application of bamboo (i.e., a wall panel) and its comparison with more common alternatives, also part of the study by Lugt [11], are not presented in this paper, therefore we refer to [20].

2.2. Environmental assessment of bamboo

2.2.1. Environmental life cycle analysis (LCA) and additional models

Life cycle analysis, or life cycle assessment (LCA), is the commonly acknowledged basis 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'). LCA was first developed in 1992 [12]. Since then it has evolved to an internationally accepted ISO-certified method (ISO 14041).

The standard LCA includes environmental effects that can be quantified. Some effects (e.g., 'deterioration of eco-systems') are ignored until a generally accepted assessment method has been developed. 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 have been developed. The validity of these models is always subject to discussion, mainly about the applied weighing method. For the environmental assessment of bamboo and its alternatives, the TWIN^{2002} model [13] was chosen, because this model is based on the latest version of the LCA-method and includes estimative methods for environmental effects that LCA lacks. Especially the deterioration of eco-systems – lacking in the standard LCA but included in TWIN^{2002} – is an important issue when comparing timber and bamboo with steel or concrete. Furthermore, the model adds a weighing methodology based on the principle of environmental costs: fictitious societal costs (monetary factors) connected to the prevention of environmental damage by certain interventions (e.g., emissions). Advantage of working with environmental costs, or eco-costs [14], is the absence of subjective weighing; disadvantage is the difficult exact determination of monetary factors. TWIN^{2002} includes recent LCA data and environmental costs of building products.

2.2.2. The functional unit

Before an environmental assessment can be executed, a general basis for the alternatives compared needs to be defined. This basis is called the 'functional unit' [15]. It is of vital importance for a correct comparison: measurements of the alternatives are determined by their technical and functional requirements (e.g., strength and stiffness). As a consequence, weaker alternatives require more material, and alternatives with a shorter life span need to be maintained or replaced more often (both leading to higher annual environmental costs).

For the bamboo culm, the functional unit chosen was column, beam and rail, as used in the pedestrian bridge in the 'Cherry blossom garden' in the Amsterdam Woods (Fig. 7), each element with its original technical requirements. Bamboo was compared with the building materials most commonly used in this application: steel, sustainably produced durable timber (species: the tropical *azobé* and European *robinia*), and concrete. Concrete was only taken into account for the function of column because it is not normally used as a line element in the other functions.

2.2.3. The process

In order to obtain the environmental score of bamboo, all steps in the production process and life span of the bamboo culm needed to be defined and analysed. For instance, for the bamboo culm this meant analysing the amount of boron used in preservation (*Boucherie method*), the amount of gasoline for the chainsaws, the number of kilometres of transport, etc. These data were retrieved through interviews with experts and literature study.

Fig. 7. Bamboo bridge in the Amsterdam Woods [photo: Pablo van der Lugt].

Data of the alternatives were already available in LCA-databases. The cooperating Dutch consulting company NIBE processed the obtained data in the TWIN^{2002} model. After this, the environmental costs of 1 kg bamboo culm over the production process could be analysed.

2.3. Financial assessment of bamboo

2.3.1. Life cycle costing (LCC)

In order to make a complete cost comparison, the method of *life cycle costing* (LCC) was used, taking into account all costs occurring during the whole life span of a product. Besides purchasing the material, costs for the building product assembly, maintenance, disassembly, and various other costs or profits in the end phase of the product (e.g., disposal of waste, yield of recycling material) are also included. To make a just comparison between alternatives, the costs of each alternative were also compared over the same reference period (annual costs).

2.3.2. The process

For the cost comparison, the same functions (column, transversal and longitudinal beam and rail) and materials (steel, *robinia*, *azobé* and concrete) were taken into account as with the environmental assessment. Following LCC, financial aspects of all steps in the life cycle of the bamboo culm needed to be analysed. Data for the costs of bamboo were obtained from the bamboo bridge project in the Amsterdam Woods. Costs of alternatives were determined through literature study and interviews with the contractors of the bridge. Alternatives are compared on the level of the elements itself (column, beam and rail).

2.4. Case study of bamboo projects in Western Europe

2.4.1. Factors of success and failure

In terms of the study presented, a factor of success or failure was defined as: "a factor that has a negative (failure) or positive influence (success) on the costs, construction time, or quality of a building project, caused by the use of bamboo, with respect to building materials more commonly used".

2.4.2. Selected projects

In the study presented, the largest bamboo building projects in Western Europe so far were analysed: the bamboo tower at the *Phenomena* exposition Zurich (1984) and Rotterdam (1985); the pedestrian bridge in the Amsterdam Woods previously introduced (1999), the ZERI-pavilion during *EXPO 2000*, Hanover (see Fig. 8); the open-air theatre during the *Festival of Vision*, in Berlin (2000; see Fig. 9); and the pavilion *Bamboo summit city* in Rotterdam (2002).

In each case bamboo was used as the main structural element. The *Bamboo summit city* was a project purely based on traditional construction techniques (lashing); the other projects combined bamboo with steel joints, poles or cables, or even reinforced concrete in joints.

2.4.3. The process

The factors of success and failure were retrieved through interviews with people involved in the building process. The interviews were analysed using qualitative research methodology. This was done through fragmentation, labelling, regulation and reduction of the text of the interviews. The found labels were analysed and finally clustered to the major factors of success and failure and their causes.

3. Results

3.1. Results of the environmental assessment

3.1.1. Environmental load during the life cycle

Fig. 10 presents the environmental load of the bamboo culm, divided in the different stages of its life cycle.

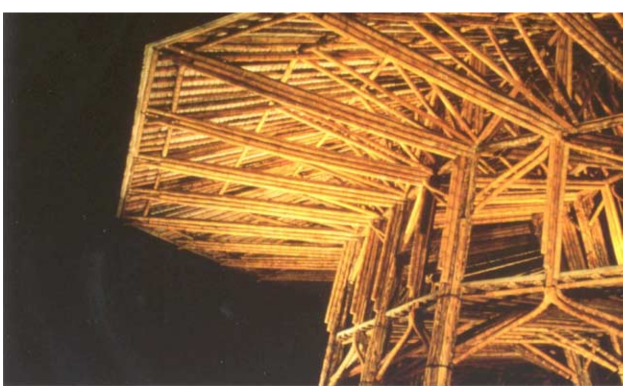

Fig. 8. ZERI-pavilion during EXPO 2000, Hanover [photo: Louis Camargo].

Fig. 9. Bamboo theatre during the Festival of Vision, Berlin, 2000 [photo: Norbert Stück].

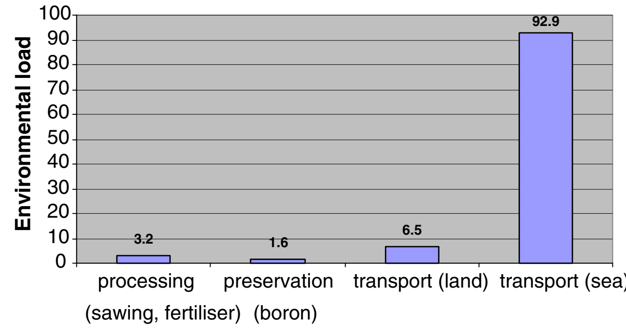

Fig. 10. Environmental load (in mPt) of 1 kg bamboo culm including transport to the Netherlands per part of the production process. Millipoints (mPts) are equal to environmental costs (in 10^{-3} euro).

It demonstrates that almost all environmental costs originate from the (sea) transport from Costa Rica to the Netherlands.

3.1.2. Annual environmental costs

In order to obtain annual values, the environmental costs of each alternative (bamboo, wood, steel and concrete) were divided by the technical life span. Other aspects, e.g., the amount of waste, recycling of the material were also taken into account. Fig. 11 presents the results. Note that the numbers are not absolute environmental costs, however represent an index. For this index, the environmental load of the alternative compared was divided by the score of the alternative with the lowest environmental impact (in all cases: bamboo), and multiplied by 100.

The data in Fig. 11 demonstrate that the bamboo culm, even when used in Western Europe, can be considered the most sustainable alternative by far in all functions. In some applications the earlier mentioned 'factor 20' 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

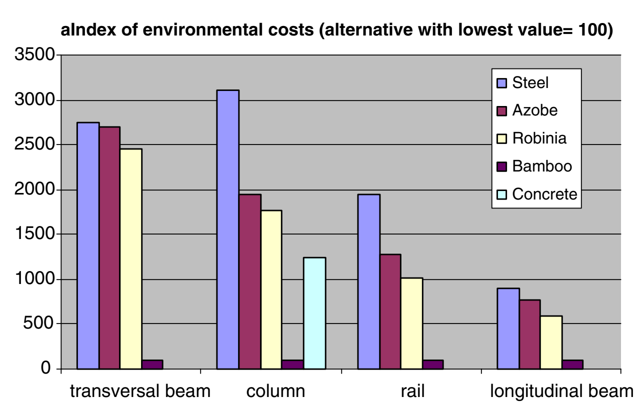

Fig. 11. Index of the annual environmental costs of the different elements of a bridge.

for the longitudinal beam. Note that the assessed timber species are sustainably produced; timber from regular, non-sustainable woods will have a considerably greater environmental impact [16].

The favourable 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 case of timber [6]. This means that, in comparison with steel, concrete and timber, for a certain load-bearing capacity, bamboo contains less material mass. The second cause is the simple, short production process of bamboo (sawing, removal of branches, preservation, drying). 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).

3.2. Results of the financial assessment

3.2.1. Purchasing costs

In terms of purchasing costs, in spite of the relatively high costs of the transport to Europe, bamboo is the least expensive in comparison with its alternatives (see Fig. 12). As with the environmental costs, the difference in costs for bamboo in the transversal and longitudinal beam is the result of the use of four culms for the longitudinal beam instead of one. Note the low purchasing costs of the standardised steel IPE-profiles, as used for the longitudinal and the transversal beam.

3.2.2. Annual product costs

In order to obtain the annual product costs, all other costs occurring during the life cycle were added to the purchasing costs (e.g., costs for assembling, maintenance, disassembling, dump). Furthermore, the costs of each alternative (bamboo, timber, steel and concrete) were divided by their life span. Fig. 13 presents the results. In terms of annual costs, steel turns out to be the most favourable building material, due to the long

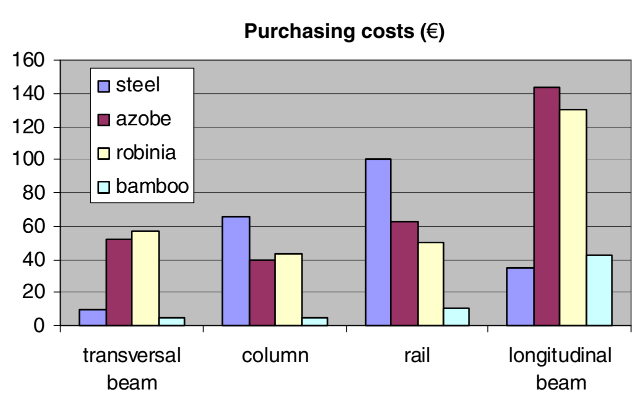

Fig. 12. Purchasing costs (in €) of the various elements and materials of a bridge.

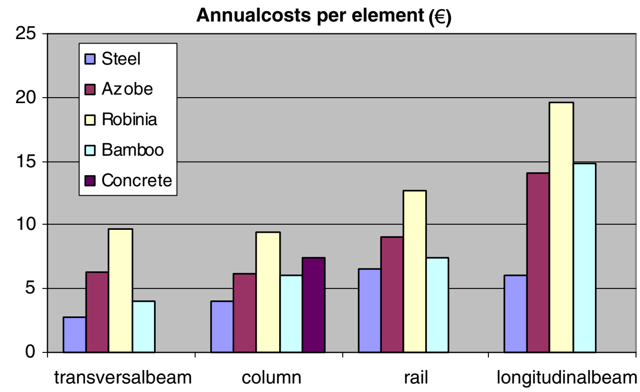

Fig. 13. Annual costs (in €) of the various elements and materials of a bridge.

life span. Because of the shorter life span and the higher labour costs of assembling and disassembling (as a result of the irregularity of the material), based on annual costs, bamboo is not the most economic alternative. The data however demonstrate that bamboo can compete with the timber alternatives.

3.2.3. Process costs

The annual product costs, as described in the previous section, were directly linked to the purchase and (dis)assembly of the various elements. However, during the financial assessment of the bamboo bridge, many additional costs were found that were linked to the use of bamboo but were not included in the annual product costs. These costs, defined as process costs, had an incidental character, i.e., they were the result of a lack of knowledge and experience with the use of bamboo. Examples of process costs are extra costs for expert consulting, intensive quality control in the country of origin of the bamboo, extra calculations, extra physical tests on a built prototype, etc.

If the process costs were included in the cost comparison, the economical performance of bamboo would be slightly worse than the alternatives. Since (the causes of) these process costs can be avoided in the future (see Section 3.3), the process costs were not integrated in the overall cost comparison of Section 3.2.2.

3.3. The case studies

3.3.1. Critical factors of success and failure

Interviews with people involved in the building process of the cases mainly revealed failure factors; only a few success factors came up. This paper will only present the factors of success and failure occurring in most of the projects studied. Through analysis of these factors, moments in the building process with a significant impact on the success of a Western bamboo project could be determined:

- The selection 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.
- The purchase of the bamboo 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, a success factor is the relatively low purchasing price of bamboo.
- In order to acquire a building permit, in all cases, extra tests and calculations were executed to determine the load-bearing capacity of the bamboo structure, leading to additional time and money expenses. Additional tests were also required, e.g., on the fire safety of bamboo. An unexpected success factor was the goodwill and cooperation of authorities involved in the issuing of the building permit.

Other factors of success – limited equipment needed, low weight of the culms – and failure – cracks and moss formation, slipperiness of wet bamboo – cannot be clustered to a particular moment in the building process.

3.3.2. Solutions

The problems described mainly originate from three bamboo-related causes:

1. the shape of the material (round, hollow and tapering);
2. irregularity of the material;
3. lack of knowledge and building codes for bamboo.

Since problems related to the shape and irregularity of bamboo are inherent to its natural character, they can only be diminished, not completely avoided. Laminating bamboo for rectangular products will diminish problems caused by the shape, however, the study presented demonstrated a relatively great increase of environmental load in that case. Using a rectangular mould during the growth of bamboo will yield rectangular cross-sections, however lead to great expenses in production [17–19].

Good plantation control and management, straightening the culms through heat treatment, as well as good quality control can diminish irregularities of the material [17–19]. In the study presented, various other recommendations were done [11]. Due to their amount and specificity, they are not presented in this paper.

Since its establishment in the year 1997, the International Network for Bamboo and Rattan (INBAR) is diminishing the lack of knowledge and building codes for bamboo. INBAR developed several international building codes for bamboo which were published in 2004 (ISO 22156:2004 (E), ISO 22157-1:2004(E)) [17–19]. Nevertheless, classification systems that are already available for timber still need to be developed for bamboo, for both the raw material (quality and strength classifications) and complete joints. These can also be expected in several years [17–19].

3.4. Conclusions

3.4.1. The environmental performance of bamboo

The environmental assessment of the pedestrian bridge in the Amsterdam Woods demonstrated the relatively small environmental load of bamboo with respect to other materials more commonly used, i.e., steel, timber, and concrete. In several functions, from a sustainability point of view, the bamboo culm is 20 times more favourable than its alternatives. This confirms the expectation of its sustainable character.

A problem with the application of the bamboo culm in Western European countries is the irregular, hollow, round form, leading to problems in joints. By laminating, a rectangular section can be created, making joints easier. However, if the bamboo culm were laminated for a flat-shaped application, i.e., a wall panel, the environmental advantage of the culm alone, will be importantly diminished [20]. These findings however do not diminish the appropriateness of the bamboo culm as a sustainable material for supporting structures, however stimulate the urge to develop better bamboo joining techniques.

3.4.2. The financial performance of bamboo

The financial assessment of the bridge in the Amsterdam Woods demonstrated that, considering purchasing costs, bamboo is by far the least expensive alternative. However, because of the shorter life span and the higher labour costs of assembling and disassembling, on an overall annual cost level, steel turns out to be the most favourable building material, due to its long life span. Nevertheless, bamboo has proven to be competitive with the timber alternatives.

3.4.3. The practical application of bamboo

Practical problems (failure factors) when using the bamboo culm in building projects 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 solutions presented. 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.

4. Discussion

4.1. Overall conclusions

The environmental and financial comparison demonstrates that bamboo can compete with building materials more commonly used in Western European 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 European 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 non-supporting or finishing material.

4.2. Restrictions to the findings

4.2.1. Applications

In the study presented, only temporary or civil structures were analysed. There are no examples of complete buildings based on bamboo supporting structures in Western Europe. Taking into account the practical disadvantages of the material, there is doubt if bamboo culms could function as a supporting structure for offices or residential buildings in Western European countries. Additional study is therefore necessary. Meanwhile, the environmental assessment results of bamboo make it a sustainable material, but only for temporary buildings or civil structures.

4.2.2. Location

The environmental assessment was based on the use of bamboo (products) in the Netherlands. When used in the country that produces bamboo (in this case Costa Rica), the environmental costs of the material will be considerably lower due to absence of sea transport. In a preliminary study concerning the complete lifecycle (including retrieval of energy when incinerating the bamboo at the end of the lifespan), bamboo even turned out to have positive environmental costs [11].

4.2.3. Data quality

As mentioned earlier, a couple of uncertainties are attached to environmental assessments, as by means of LCA. First, the purveyor or producer of bamboo could not always provide the required data, making assumptions necessary. Second, the reliability of some of the used data is also debatable. In order to compensate for this, the environmental assessment of bamboo took place following a *worst case scenario*. Therefore, results are presumably less favourable for bamboo than in reality. Moreover, some environmental aspects that could be favourable to bamboo, e.g., the annual production of biomass of a bamboo plantation (which is 3 times as great as for the average timber productive forest, see Table 1), were not included in the assessment.

Table 1
Annual production of plantations for producing wood and bamboo [17,19]

	Green (total)	Dry (total)	Green (culm only)	Dry (culm only)
Annual production (tons/ha)				
Bamboo	78.3	47.4	55.7	36.0
Wood	17.5	13.5	14.0	10.8
Ratio bamboo/wood	4.5	3.5	4.0	3.3

4.3. Recommendations for further research

The environmental and financial comparison has been conducted for bamboo in a very specific application (column, beam and rail, as used in the pedestrian bridge in the Amsterdam Woods). For a broader perspective of the environmental performance of bamboo (products), additional environmental assessments by LCA are needed:

- with data from other species, and from more plantations 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 (e.g., using the bamboo culm inside buildings, industrial applications, e.g., bamboo strips, parquet, panels);
- 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 bamboo joints with different building techniques (e.g., lashing, concrete joints);
- in another application (using the bamboo culm inside buildings for 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 Western countries, this research can be repeated for countries outside Europe (e.g., Canada, USA).

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