ENGINEERED BAMBOO IN EUROPE: *A STUDY INTO PRACTICAL APPLICATION OF MOSO BAMBOO-BASED BUILDING ELEMENTS IN EUROPEAN ARCHITECTURE*

Luc Thomassen, BSc
Faculty of Architecture & the Built Environment, Delft University of Technology
Julianalaan 134, 2628BL Delft

ABSTRACT

Introduction: *Engineered Moso bamboo has favorable mechanical properties and shows great potential for large scale application in European architecture due to its high renewability. However, lack of standardization and coherence in test data strongly hinders its practical application.*
In this research paper, the practical application potential of Moso bamboo in European architecture is investigated and its design implications are quantified.

Methods: *The study was conducted through literature review and through a quantitative comparison study, in which Moso bamboo building elements were compared to equally performing building elements, made from other commonly used materials in Europe.*

Conclusion: *Moso bamboo can be engineered into a number of forms, each of which is well-suited for a different particular application. Additionally, its unrivaled renewability, relatively low cost and excellent mechanical performance can give Moso bamboo a significant advantage over other renewable and non-renewable building materials. As such, large-scale application within European architecture as an alternative to wood-based or unrenewable materials appears viable.*

Product: *The data and conclusions from the quantitative comparison study (Appendix 2) were compiled into a practical tool that provides designers with relevant information about using bamboo-based or other renewable building materials and helps them quantify their material design choices.*

KEYWORDS: *Moso Bamboo, building elements, construction, architecture, design tool, quantitative comparison, sustainable architecture, renewability*

0. Contents

I. INTRODUCTION

Moso bamboo has favorable mechanical properties for high-density construction applications such as a very high strength to weight ratio (van der Lugt et al., 2006). Additionally, the Phyllostachys family, to which Moso bamboo belongs, is proven to be the fastest growing plant on Earth (Van der Lugt, 2017). These properties make bamboo very promising as a building material. Large-scale bamboo farming, however, is traditionally mainly done in mainland China, making it a CO2 intensive material to use in Europe when taking shipping into consideration (Van der Lugt & Otten, 2006). In the academic world, this has led to bamboo often being discarded as not sustainable.

Recently, initiatives have been taken to farm bamboo in Europe. Bamboologic (www.bamboologic.eu) and Onlymoso (www.onlymoso.com) are examples of companies that do this. European Moso bamboo has similar properties to the bamboo grown in China, making it applicable in the same use-cases. (BambooLogic, n.d.; Onlymoso, n.d.) Additionally, there are a number of positive local side-effects from the farming of bamboos, such as absorption of CO2 and NOx, desalinization of soil as well as economic opportunities (Van der Lugt & Vogtländer, 2014). This shines a new light on the use of bamboo in Europe, as it could be a sustainable large-scale solution and a viable addition to engineered pinewood construction in many cases.

However, as of yet, the main problem hindering the use of Moso Bamboo on a large scale is severe lack of industrialization and standardization (van der Lugt et al., 2006; Van der Lugt, 2017). Numerous studies have been done on the use of raw bamboo in load bearing structures or as supporting structures, especially in China (Chung & Yu, 2002; Widyowijatnoko & Harries, 2020; Xiao et. al., 2008). The knowledge in this field is established well enough to have practical implications. This becomes clear through the many case studies using raw bamboo (Xiao et. al., 2008; Van der Lugt, 2017). On the other hand, very few case studies use engineered forms of bamboo to their full potential. This is not due to a lack of knowledge: there is plenty of information about the possibilities of engineering bamboo (Mahdavi, 2011a; Mahdavi, 2011b; Sinha et. al., 2013; Sharma et. al., 2015). However, the step from theory to practical application, as has already been done with raw bamboo, has not been taken with engineered bamboo.

Therefore, in order to make the use of engineered Moso bamboo more standardized and accessible as a building material, the existing knowledge base about engineered bamboo needs to be extended to the applied context. The transition from engineered bamboo as a material, which is already thoroughly researched, to the practical application possibilities into architecture and the implications this has on a design is the gap this research paper aims to bridge.

Research question:

Can Europe-produced Moso bamboo be optimally engineered into industrialized building elements for use within common typologies and is it a viable alternative to other renewable building materials?

Sub questions:

1. What are the mechanical properties of Moso bamboo and how can the raw material be processed into engineered forms of bamboo?

2. What are the advantages and disadvantages of Moso bamboo building elements when compared to other commonly used building materials?

3. What is the optimal form of bamboo to use for each building element type, with regards to the mechanical properties, sustainability, production cost, safety and building codes?

4. What is a suitable design strategy for the optimal use of said bamboo building elements for architectural applications within Europe? (Design tool)

II. Moso bamboo properties

2.1. Growing process

Although comparable to wood in its chemical composition, bamboo differs quite a lot from wood as a plant. This is because bamboo is a form of grass and as such grows in a vastly different way to trees. Trees function largely individually, with their own root system, trunk and leaf structure. Bamboo plants, however, are interconnected. (Van der Lugt, 2017)

The stems that are visible above ground appear individual, but they make use of a shared root system, consisting of rhizomes (Trujilo & Lopez, 2016). This shared root system enables the bamboo stems to share resources, whether that be nutrients or produced gases. This, in turn, makes it possible for adult stems to assist the growth of young stems by providing them with an abundance of nutrients and CO2, vastly accelerating the growth process and making it less dependent on atmospheric conditions (Van der Lugt, 2017). For this reason, the growing speed of bamboo is mainly limited by sunlight and rainwater, whereas most other plants are limited by the CO2 concentration in the air (Laing et al., 1974). As a consequence, bamboo has an unparalleled growing speed, in some cases up to 30m in the first year, along with great carbon and nitrogen sequestration (Song et al., 2011).

That said, the bamboo stem is not yet ready for harvest after its first year as it is still herbaceous at that point. After an additional 3 years, in which the stem hardly grows in length, it becomes thicker and more wood-like, making it ready for harvest (Trujilo & Lopez, 2016). Harvesting should be done to roughly half of the total production capacity, allowing the remaining half of the stems to aid the new culms to grow quickly. As a rough estimation, therefore, a full Moso bamboo production forest can be renewed fully every four years, split up into half-capacity harvests every two years (Kuehl & Yiping, 2012)

2.2. Anatomy of the bamboo stem

The anatomy of the bamboo stem also differs from the anatomy of a wooden trunk. Firstly, a bamboo stem is hollow and cylindrical. This allows the stem to be light, but still strong enough to handle the wind forces. In cross-section, the stem has a varying density. The outside of the stem has a higher fiber density than the inside, making it stronger without wasting any material. (Trujilo & Lopez, 2016; Van der Lugt, 2017)

In the length direction, there are some variations in the stem as well. Again, the fiber density differs, as well as the moisture content. This has implications for the elasticity of the stem. On the bottom of the stem, for example, where most of the bending moment is expected, the moisture content is higher, providing higher elasticity and less stiffness. (Trujilo & Lopez, 2016)

While these variations in the culm allow the plant to function well in its natural environment, they present challenges when considering bamboo as a building material. It was mentioned earlier that lack of standardization was one of the main problems hindering the large-scale application of Moso bamboo as a building material. The lack of standardization is mainly caused by the significant variations in the stem anatomy. (Harries et. al., 2020)

2.3. Mechanical properties

Despite the variations in stem anatomy, variation in the chemical composition of the material is relatively small. On average, the Moso bamboo stem consists of roughly 40% cellulose, 10% vascular bundles and 50% parenchyma tissue, which is largely lignin. (Van der Lugt, 2017) Of these contents, the vascular bundles are weak tissue and as such provide no mechanical advantage. The main strength is obtained from the parenchyma tissue and cellulose. (Van der Lugt, 2017) Additionally, the cellulose from unused parts of the culms can be used to produce other products like paper or even biobased resins. (Ferdosian et. al. 2016)

The mechanical properties of a raw bamboo stem are difficult to define because of the afore-mentioned variations along the length of the culm. That said, most of these variations relate to the moisture content variation. If the stem is dried to minimize the moisture content, the mechanical properties become more uniform, although the differences in fiber density remain. (Trujilo & Lopez, 2016) As a result, the lowest mean values from testing, provided a certain moisture content, become the characteristic value of the material. ISO/DIS 22156, established in 2014, has been working on structural standards of bamboo for use within Europe. In ISO/DIS 22156:2020, which is the most recent version of the standard, the value of standardized moisture content is repeatedly emphasized and service classes are defined for different levels of moisture content (ISO/TC 165, 2020).

Although multiple tests have been conducted to establish mechanical properties of the raw bamboo stem, they often only cover certain aspects of the material. This means that in order to achieve a full overview of mechanical properties, one has to compare multiple test results. In practice, this means that the test method or moisture content is not always consistent when comparing values. Chung & Yu (2002) do apply a consistent testing method and a controlled moisture content across different tests.
However, their suggested characteristic values do not correlate to the afore mentioned service classes as defined in ISO/DIS 22156:2020, hence they are not well applicable to the European context. From their test data's mean minimal values, however, a number of different values can be distilled that do correspond to the ISO service classes. These values are presented in Table 1.

ISO Service Class	**Moisture Content**	**Compressive strength (N/mm^2)**	**Bending strength (N/mm^2)**	**Compressive Young's Modulus (kN/mm^2)**	**Bending Young's Modulus (kN/mm^2)**
-	5%	115	50	6	9
SC1	12%	75	50	5,5	8
SC2	20%	65	50	5	7,5
SC3	>20%	40	50	4,5	6,5

Table 1: Characteristic mechanical properties of bamboo stems (Chung & Yu, 2002) categorized by ISO/DIS 22156:2020 service class

It must be noted that these are 5^{th} percentile mean minimum values. As such, they represent the lowest possible strength the material will have and thus the only safe standardized value to use. Upon architectural application, safety correction factors must be added on a building-element scale as defined in ISO/DIS 22156:2020.

Other factors to note when considering raw bamboo as a building material are the geometric inconsistencies and the joints. The geometric inconsistencies can make the material difficult to implement in an architectural manner, while the joints are often difficult to make or cause weakpoints, leading to lower characteristic mechanical values (Widyowijatnoko & Harries, 2020). However, there are engineered joints that cope well with the geometric and structural challenges, such as a modified Nienhuys joint (Widyowijatnoko & Harries, 2020).

III. ENGINEERED MOSO BAMBOO

One of the main problems of Moso bamboo when applied into architecture is its lack of standardization. The geometry is inconsistent, the joints are complicated, difficult to mass-produce and the characteristic mechanical values are decreased significantly due to the great variation in the material. These factors make the construction process complicated and increase cost significantly.

Because of this need for standardization, engineered bamboo has developed much in the last ten years and research into individual methods is quite extensive. However, there is little coherence in the academic discussion. Used terms are often not clearly defined and because of this, used incorrectly, which causes ambiguity surrounding engineered bamboo. The main aim of this chapter, therefore, is to shed light on the different production methods and the advantages and disadvantages associated with different forms of engineered bamboo. Knowledge of the production process and composition helps better understand the properties of the material on a building element scale.

3.1. Shredding-based

Shredding-based bamboo products have been used for a long time, often as a cheap or local -in Asia- alternative to pinewood fiberboards (Van der Lugt, 2017). There are three main products that can be made using shredding-based methods (E.P.A., 2002):

1. LDF (Low density fiberboard): Is produced by harvesting bamboo stems and drying them for 3 months. After this, the stems are fed through a shredding machine and converted into medium size particles. These are mixed with resin and pressed into a mold. The outcome is a large board that can be cut to size. (E.P.A., 2002)

2. MDF (Medium density fiberboard): MDF is produced similarly to LDF, but there is an extra step to the shredding process. After shredding, the medium size particles are fed through a defibrator machine, creating a wood-pulp, increasing density. This pulp is then pressed into a mold along with resin. The outcome is a large board that can be cut to size. (E.P.A., 2002)

3. HDF (High density fiberboard): HDF is to a large extent produced in exactly the same way as MDF, but it is pressed using more heat and with higher pressure. This further reduces the resin content to, causing a higher density and a stronger material. The outcome is again a large board that can be cut to size.

The advantages of shredding-based materials are that they are fast and cheap to produce, while providing a decent amount of strength. However, because the fibers are shredded, they lose their directional strength. For this reason, a fiberboard will always be much weaker than a product that keeps the full fibers intact. They are well suited to low-stress applications.

3.2. Shaving- / strand-based

Shaving-/strand-based bamboo products do take advantage of directional strength, conserving the longitudinal fibers from the bamboo stem. There are multiple ways to achieve this. Contrary to what the term implies, shaving-based materials are not produced by shaving fibers from the surface of the stem. In reality, two different methods are used (Mahdavi et. al., 2011b). Firstly, the stem can be cut in the longitudinal direction, leaving geometrically consistent strands. Secondly, the stem can be pressed flat, naturally splitting the bamboo and leaving geometrically inconsistent strands. Thus, in reality, the end result is always a form of strand. From this point onwards, these production methods will therefore simply be referred to as strand-based. (Mahdavi et. al., 2011b)
Because strand-based products start with a number of small strands, they all rely on a process of layering/lamination to achieve the desired geometry. There are multiple ways to achieve this, but there are currently four production methods that are used on an industrial scale (Mahdavi et. al., 2011b).

1. **Method 1 (Lee et. al., 1998) – *Flattened bamboo LBL*:**
   Whenever laminated bamboo lumber (LBL) is mentioned in literature, it generally refers to LBL manufactured using this production method. In reality, however, methods 3 and 4 are also forms of LBL.
   The bamboo stem is dried and split in half, after which the splits are flattened in a press. The flattened splits are passed through a planer to remove wax and silica from the surfaces and improve resin adhesion. Adhesive is added to the surfaces, after which the splits are stacked on top of each other and pressed for twelve hours. The flattened strips can also be used in lower grade flattened bamboo

products like flooring or boards. They are then simply referred to as Flattened bamboo (Mahdavi et. al., 2011b). To produce LBL, however, multiple layers of Flattened bamboo are laminated.

2. **Method 2 (Nugroho & Ando, 2001) – *Strand woven bamboo / SWB***:
   This is often sold as strand woven bamboo, although sometimes also referred to as scrimber.
   The bamboo stem is firstly cut into 8 pieces, fed through a roller press and hot pressed to remove voids (Houben et. al., n.d.). This creates thin, fibrous mats, which are planed to remove wax and silica layers, covered in resin and either cold-pressed or hot-pressed, depending on the desired end-product's density, hardness and moisture resistance. (Mahdavi et. al., 2011b)

3. **Method 3 (Rittironk & Elnieiri, 2008; Sulastiningsih & Nurwati, 2009) – *Plybamboo LBL***:
   This method differs significantly from the other methods and was developed mainly to reduce glue content. It is produced by firstly splitting the stem into strips. Each of these strips is individually planed to create square edges. The surfaces of the square strips are covered with resin, after which the strips are carefully aligned and clamped to dry. (Mahdavi et. al., 2011b). Again, the sheets or plies can be used for non-structural application. To produce LBL, multiple plies are laminated.

4. **Method 4 (Xiao et. al., 2013) - *Gubam*:**
   This method has similarities to method two but more favorable from a production perspective. It was developed by the company Glubam, so products produced with this method are also generally referred to as Glubam. Do not confuse it to be the bamboo equivalent of Glulam however, as it is different.
   It is produced by cutting the bamboo stem into small strands. These are mixed to distribute fiber density throughout the material. The strands are placed parallel to each other and connected with string to create mats. The mats are saturated with resin and arranged on top of one another. The orientation of this arrangement can vary depending on the end-product, similar to carbon fiber. The stacked mats are pressed to create thin, plywood-like sheets, called Glubam sheets. These sheets can be used to create all sorts of products, like beams, cross-laminated panels, or simply to be used as bamboo plywood. (Xiao, 2020)

Each method has advantages and disadvantages when compared to others. Method 1 (Lee et. al., 1998), although the oldest method, is still very quick and cost-effective to produce, making it an excellent low-cost option. Method 4 (Xiao et. al., 2013), appears to have important advantages regarding production scalability. There is almost no manual labor involved, the fiber density is well distributed across the material and many different products can be created using the same base-material production line. Its biggest drawback, however, is its high glue content. Typical resins used for laminated wood- and bamboo products are phenol or resorcinol formaldehydes and cyanoacrylates (Sinha et. al., 2013). Both are petroleum-based and significantly decrease sustainability of laminated bamboo products. For this reason, method 3 (Rittironk & Elnieiri, 2008; Sulastiningsih & Nurwati, 2009) aims to greatly reduce glue content by using geometrically consistent strips, decreasing adhesion surface and preventing voids in the material. Production efficiency of this method is relatively low, increasing cost. Recently, however, progress has been made in the development of cellulose based resins, putting them on par with cyanoacrylate resins and a step ahead of formaldehyde-based resins (Ferdosian et. al. 2016). It might be worth reconsidering if high glue content is a disadvantage, provided cellulose-based resins could be used. These can namely be produced from bamboo and wood production-waste, as well as paper waste (Ferdosian et. al. 2016).

3.3. Engineered bamboo products

Engineered bamboo can differ vastly and thus can be applied in a multitude of use-cases. In this paragraph, the afore mentioned types of engineered bamboo are summarized and elaborated upon, along with their commercial terminology.

Commercial Terminology	**Use case and production method**
Bamboo LDF	Low quality finishing material *Product of LDF production method*
Bamboo MDF	Medium quality finishing material *Product of MDF production method*
Bamboo HDF	High quality finishing material

	Product of HDF production method
Flattened bamboo	Medium quality finishing material *Non-structural product of Lee et al. (1998) production method*
Flattened bamboo LBL	Structural material *Laminated structural product of Lee et al. (1998) production method*
Plybamboo	Medium/High quality finishing material *Non-structural product of Sulastiningsih & Nurwati (2009) production method*
Plybamboo LBL	Structural material *Laminated structural product of Sulastiningsih & Nurwati (2009) production method*
Glubam	Structural material *Laminated structural product of Sulastiningsih & Nurwati (2009) production method*
SWB (cold pressed)	High quality finishing & structural material *Structural product of Nugroho & Ando (2001) production method or similar*
SWB (hot pressed)	Very high quality finishing & structural material *Structural product of Nugroho & Ando (2001) production method or similar*

In the table above, all forms of engineered bamboo that are produced on an industrial scale are summarized. These will also form the basis for a comparative study conducted in Chapter 4.

3.4. Mechanical properties of structural engineered Moso bamboo

There is a significant lack of consistency in existent mechanical test data, due to an abundance of different test-protocols (Sharma et. al., 2015). A full summary of mechanical properties per method is therefore difficult to provide. For the purposes of this paper, only values using the ASTM D143 and ASTM D198 test methods (ASTM, 1998; 1994) have been used as it is most common among the literature and as such the most consistent. ASTM test methods generally don't vary greatly from ISO test methods. As such, these numbers also give a reasonable estimation of values obtained with ISO test methods.

Product	**Compressive strength (×10^6 N/mm^2)**	**Bending strength (×10^6 N/mm^2)**	**Young's Modulus (×10^6 kN/mm^2)**	**Density (kg/m^3)**
Flattened bamboo LBL[1,2]	59,0	97,0	8,4	850
SWB (cold pressed)[1]	52,0	83,5	10,9	1080
Plybamboo LBL[2]	63,0	87,8	9,8	700
Glubam[3]	51	99,0	9,0	880

Table 2: Characteristic mechanical properties of structural engineered bamboo products, obtained with ASTM D143 and ASTM D198 test protocols

[1] Mahdavi et. al. (2011); [2] Sinha et. al. (2013); [3] Xiao et. al. (2013; 2020)

Table 2 shows the 5th percentile mean lowest values, which give a good indication of characteristic values that may be used for further calculation. These values are significantly lower than those of the raw bamboo, but they are far more consistent and evenly distributed along the building element (Harries et. al., 2020).
Noteworthy is the relatively good compression strength of methods 1 and 3. In both of these methods, the stem undergoes little destructive alterations and as a result, the fibers can remain bound together on a cellular level. This better maintains the strength of the original stem (Trujilo & Lopez, 2016). Additionally, the relatively low glue content and high fiber content in method 3 improves its compressive strength.
The bending strength of methods 1 and 4 is significantly higher than that of methods 2 and 3. This is, most likely linked to the lower Young's modulus, as was the case with the raw bamboo stem, in which it

was observed that the lower Young's Modulus caused the material to bend more, rather than break. (Trujilo & Lopez, 2016)

Method 2 appears to have no significant advantages from a mechanical standpoint, whilst being relatively dense and expensive to produce due to the pressing production method (Mahdavi et. al., 2011b). It does, however, have increased resistance against wear, moisture and organisms (MOSO®, 2020).

IV. BAMBOO BUILDING ELEMENTS COMPARED TO OTHER MATERIALS

In the previous chapters, the properties of bamboo and the possibilities of converting it into engineered building elements was addressed. In this chapter, a comparative study will be conducted on a building-element scale to determine how Moso bamboo performs in comparison to other commonly used building materials. For the purpose of comparison, building elements are categorized into two groups, each requiring a different type of comparison:

1. Structural: This category consists of building elements that play a role in the transmission of forces on a building scale. This includes the main load bearing structure as well as substructures. Examples of structural building elements are columns, beams and load bearing walls.

2. Finishing: This category consists of building elements that the user interacts with directly. Examples of such building elements are wall finishings, flooring and windowframes.

The building materials will be evaluated on use-specific performance aspects, relative renewability, and ECO-costs, as used in the IDEMAT life-cycle-analysis system. The IDEMAT system not only takes CO2 balance into consideration, but also other factors that have environmental impact. (Aiming Better, 2019)

4.1. Structural

4.1.1. Methodology

Structural building elements can be difficult to compare and are sometimes compared wrongly. This is because there is a multitude of factors that influence a structural building element, such as bearing capacity, applied load, span, cross-section, Youngs modulus and density. Commonly, only one or two of these properties, such as MOR or strength-to-weight ratio, are used in comparative analysis. However, when comparing equally performing building elements is the goal, a method must be used that takes all relevant factors into account. To achieve this, structural elements are first split up into bending elements (beams) and compressive elements (columns, walls), because they experience different loads.

4.1.1.1. Bending element study 1 (rectangular cross sections: beams & floor elements):

With bending elements, there are two ways performance can be compared. The first way is using the required Section Modulus (*W*). The required section modulus (*W*) depends on the applied moment (*M*) and the allowable stress of the material in perpendicular direction (σ) and is calculated using the formula $W = \frac{M}{\sigma}$. The bending moment (*M*) is dependent on the length of the element, as well as the applied force. Because these values are the same for every building element, *M* can be considered a constant in our analysis and will be referred to as K_1 . The section modulus (W) can then be expressed as

$$W = K_1 \times \frac{1}{\sigma}.$$

Because we are looking to compare properties like volume, weight and eco-costs of equally performing building elements, the relative area of cross-section (A) is required. To find A, we use the formulas $W = \frac{1}{6} \times b \times h^2$ and $A = b \times h$. Because $\frac{1}{6}$ and b are the same for all elements, their product can be defined as a new constant (K_2) from the formulas, leaving $W = K_2 \times h^2$. This means that $h^2 = \frac{W}{K_2}$ and thus $h = \sqrt{\frac{W}{K_2}} = \frac{\sqrt{W}}{\sqrt{K_2}}$. As $\frac{1}{\sqrt{K_2}}$ is also a constant (K_3), we have $h = K_3 \times \sqrt{W}$ and as such

$A = b \times K_3 \times \sqrt{W} = b \times K_3 \times \sqrt{K_1} \times \sqrt{\frac{1}{\sigma}} = K_4 \times \sqrt{\frac{1}{\sigma}}$ where K_4 is constant across all building elements in our comparison. This formula is used to compare needed cross sections, without disregard for the added value of height in the profile, as is often the case. The area of cross-section can be used combined with density, to compare the volume, weight, eco-costs and renewability of equally performing structural building elements.

In each comparison, we calculate the ratios $W_{material\,1}$ / $W_{material\,2}$ and $A_{material\,1}$ / $A_{material\,2}$ for the respective materials. As K_1 is the same for all elements, and so is K_4, the constants K_1 and K_4 cancel out in these ratios, irrespective of their numerical value. To be able to perform the numeric calculations with an Excel table, all constants were set to the numerical value 1.

4.1.1.2. Bending element study 2 (beams with absolute proportioning):

The biggest advantage of the method described above is also its biggest downside. The fact that the comparison is independent of cross-sectional profile shape leaves materials that can be shaped more efficiently, such as steel, at a significant disadvantage. A second analysis, therefore, is conducted to compare the effect of cross-sectional profile. In this analysis, hybrid beams are also implemented.

Because aspects like width (b) are taken out of the equation with method 1, it is irrespective of profile shape and as such applies to every situation. However, because we are now looking to implement different geometries into the comparison, we can no longer work solely with ratios of the section modulus (W). A value of the section modulus can be achieved by a multitude of different geometries, each with different cross-sectional area's (A) depending on shape. Therefore, to enable us to compare the effect of profile shape, absolute numeric values of W are required. As a consequence of the relation $W = \frac{M}{\sigma}$, the bending moment (M) is fixed upon selecting a baseline material with associated bending strength (σ) and a baseline geometry (W). This makes comparisons using method 2 specific to one use-case and less generic than method 1.

A steel (s355) HEM-220 beam was chosen as a baseline, because it represents a very common use-case. The HEM-220 beam has a section modulus ($W_{steel;HEM-220}$) of $1{,}2 \times 10^8\ mm^3$. We can now use the formula $W_{steel;HEM-220} = \frac{M}{\sigma_{steel}}$ to calculate M for our chosen use-case as

$M = W_{steel;HEM-220} \times \sigma_{steel} = (1{,}2 \times 10^8) \times 355 = 4{,}3 \times 10^{10}\ Nmm.$

With the bending moment fixed at this value, representing our use-case, we can calculate W_{mat} for each material using the formula $W_{mat} = \frac{M}{\sigma_{mat}} = \frac{W_{steel;HEM-220} \times \sigma_{steel}}{\sigma_{mat}}$.

Depending on profile, the associated cross-sectional area (A_{mat}) is then found in steel-tables or calculated manually. Each of these properties is then again divided by the baseline values of steel, to make them relative again.

$A_{mat;relative} = \frac{A_{mat}}{A_{steel}}$ and $h_{mat;relative} = \frac{h_{mat}}{h_{steel}}$.

Using these values, relative volume, weight, renewability and ECO-cost can again be calculated. For the hybrid materials, the same methodology was used, but adjusted W values were first calculated using flange-width correction. Additionally, in the weight and ECO-cost comparison, the percentage of each material within the hybrid is accounted for, based on the relative area of each material in relation to the total cross-sectional area. The same is then done with density, to determine the combined weight and ECO-cost.

4.1.1.3. Compression element study (columns, load bearing walls & stability elements):

The performance of compression-based elements such as columns and load bearing walls is far less complex to compare, as their required cross-section is based on the compressive strength, which is a material property. As such, the formula $\sigma = \frac{F}{A}$ can be used. Given that the force (F) is the same for all elements, it can be defined as a constant (K_5). The required surface area (A) can be expressed as $A = \frac{K_5}{\sigma}$. Again using ratios of the cross-sectional area, a comparison can be made of relative volume, weight, renewability and ECO-cost.

4.1.2. Source Data

See Appendix 1

4.1.3. Results Beams & Floors (method 1)

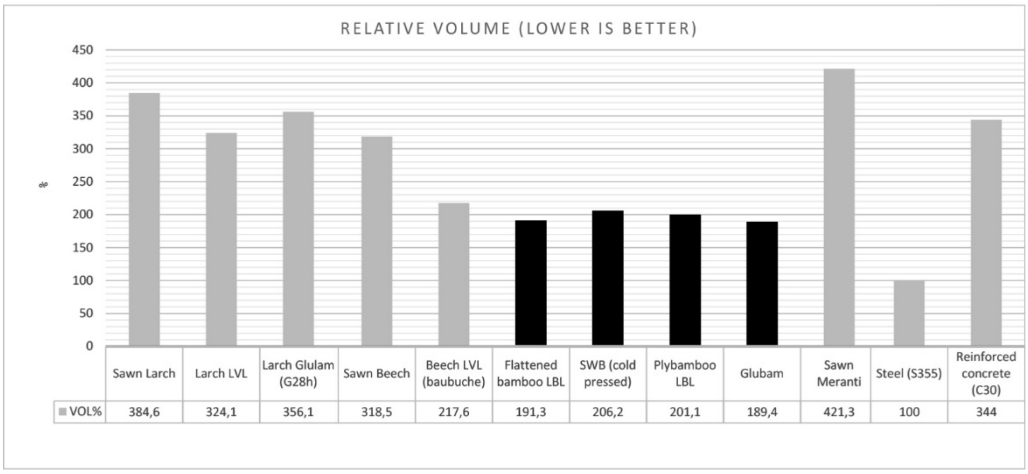


Figure 1: Relative volume comparison. Bamboo building elements perform better than concrete- and Larch-based alternatives.

Figure 1 shows the relative volume, with respect to s355 steel, of bending elements using analysis method 1. It becomes clear that the bamboo-based building elements perform excellently when compared to Larch-based building elements. Compared to reinforced concrete, the bamboo-based building elements require roughly half the thickness, making bamboo CLB floors a viable alternative to concrete floors. Steel still requires the least volume, but the bamboo building elements do approach its capabilities and more so than commonly used Larch alternatives. The excellent performance of Beech LVL is also noteworthy.

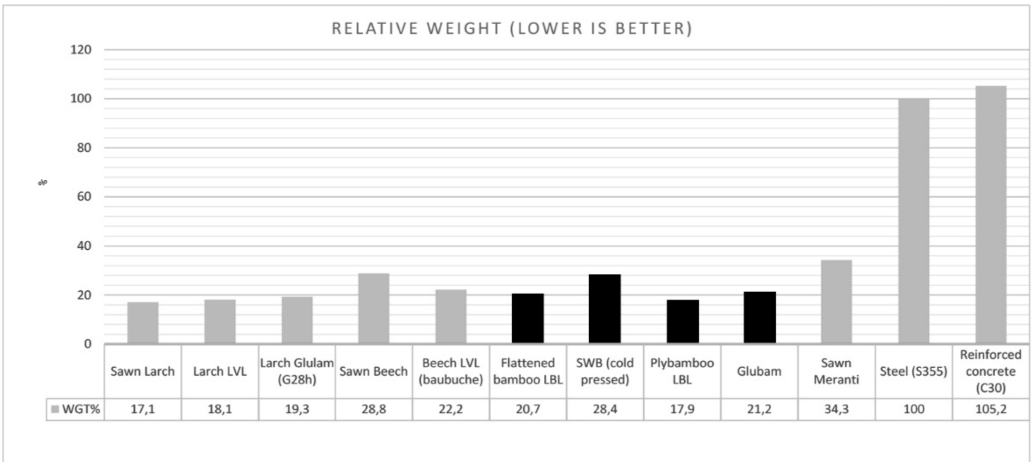


Figure 2: Relative weight comparison. Bamboo building elements are on par with Larch- and Beech-based alternatives and significantly lighter than hardwood, steel and concrete.

Figure 2 shows the relative weight, with respect to s355 steel, of bending elements using analysis method 1. It becomes clear that weight-wise, wood- and bamboo-based building elements perform much better than both steel and reinforced concrete. This enables particularly lightweight constructions. The performance of the bamboo-based building elements is on par with the wood-based building elements, but not better.

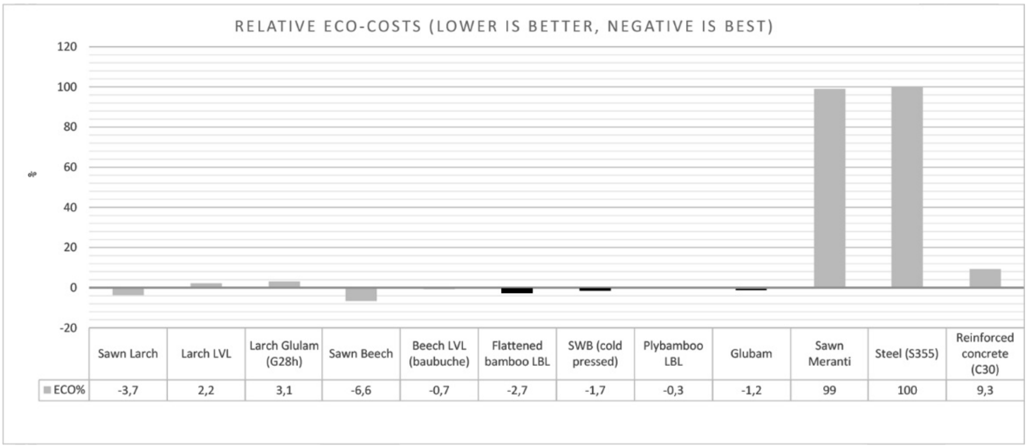


Figure 3: Relative ECO-cost comparison. All wood- and bamboo-based products perform much better than hardwood and steel and slightly better than concrete.

Figure 3 shows the relative ECO-cost, with respect to s355 steel, of bending elements using analysis method 1. All larch-, beech- and bamboo-based building elements perform much better than hardwood and steel. Reinforced concrete performs better than expected and is not that much worse than some engineered larch products. The best ECO-cost is achieved by sawn Beech. Bamboo-based elements produced in Europe, however, are roughly on par with the ECO-cost of equivalent Beech products and slightly better than Larch products.

4.1.4. Results Beams (method 2)

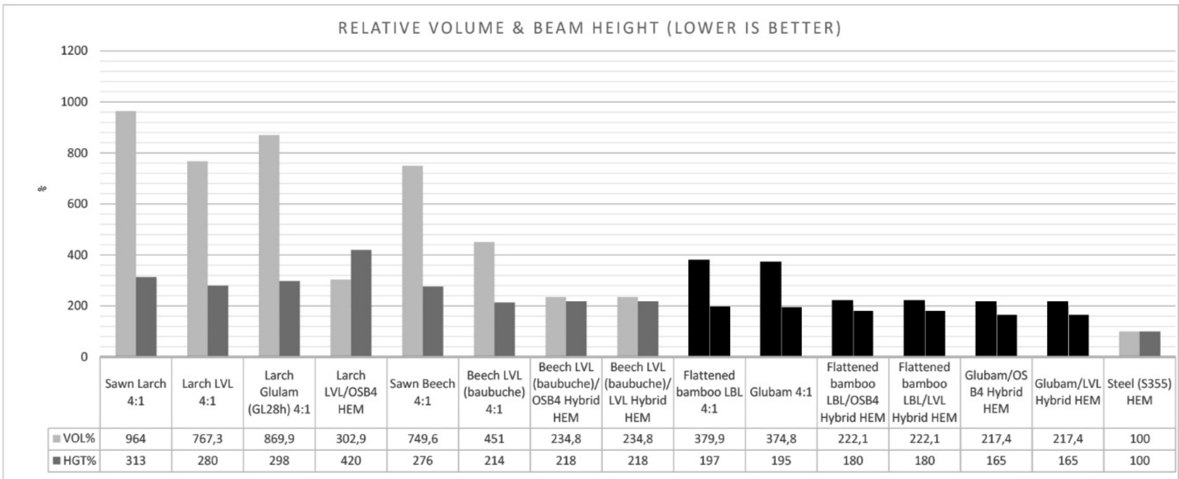


Figure 4: Relative volume & height comparison. Bamboo performs the best overall and it, along with Beech, performs significantly better than Larch.

Figure 4 shows the relative volume and height, with respect to s355 steel, of bending elements using analysis method 2. It firstly becomes clear that there are large variations in volume associated with cross-sectional profile. HEM-profiles require much less material, but especially with larger profiles, this is not reflected in a significant beam height difference. Apart from steel, the bamboo-based building elements perform best, requiring the least volume and the least height. They are closely followed by the Beech-based elements. Larch elements perform significantly worse and require a large amount of material.

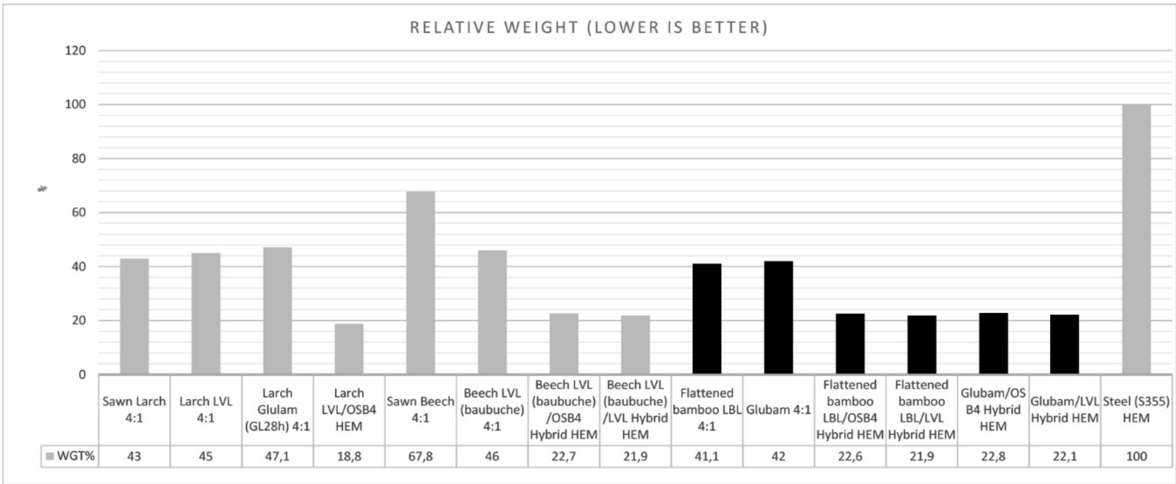


Figure 5: Relative weight comparison. The HEM-profile and hybrid material significantly reduce weight. Larch hybrid beams perform best, with Beech hybrid and bamboo hybrid beams roughly on par.

Figure 5 shows the relative weight, with respect to s355 steel, of bending elements using analysis method 2. It becomes clear that the weight-advantage of Larch over bamboo disappears due to the disproportionately large amount of volume needed for Larch elements with the 4:1 profile. The Larch hybrid HEM does perform very well, regarding weight. For small spans, this would therefore be the best performing element. The bamboo-based building elements perform on par with equivalent wood-based elements. Steel compares poorly, requiring roughly five times the weight.

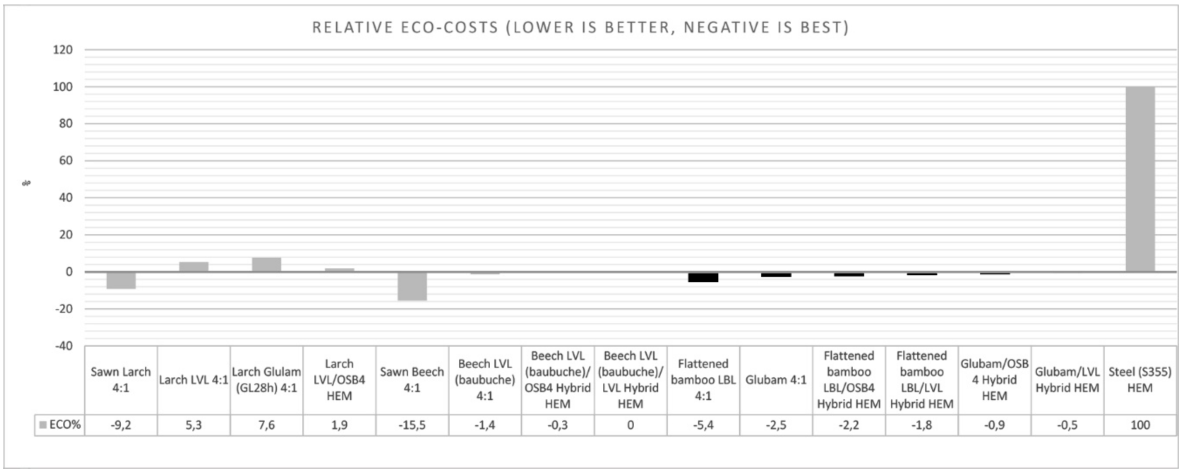


Figure 6: Relative ECO-cost comparison. Sawn wooden beams have a significant ECO-cost advantage. Engineered bamboo performs better than engineered forms of wood.

Figure 6 shows the relative ECO-cost, with respect to s355 steel, of bending elements using analysis method 2. The results are largely in line with the results from analysis method 1, although sawn Beech and Sawn larch have by far the best ECO-cost performance, due to their negative ECO-costs and high required volume. The Europe-produced bamboo elements perform better than their equivalent wood-based counterparts and Flattened bamboo LBL, which is an engineered bamboo, even approaches sawn larch.

In summary, bamboo-based bending elements (beams & floors) perform better than wood- and concrete-based alternatives regarding volume and they perform on par with wood-based alternatives regarding weight, outperforming concrete and steel. Additionally, the ECO-cost performance of Europe produced bamboo elements is better than equivalent Larch- or Beech- based products, but worse than that of sawn wood. This makes bamboo-based bending elements especially suitable for high-stress and/or large-span applications, in which high mechanical performance is required, but not at the cost of sustainability.

4.1.5. Results Columns & Load bearing walls

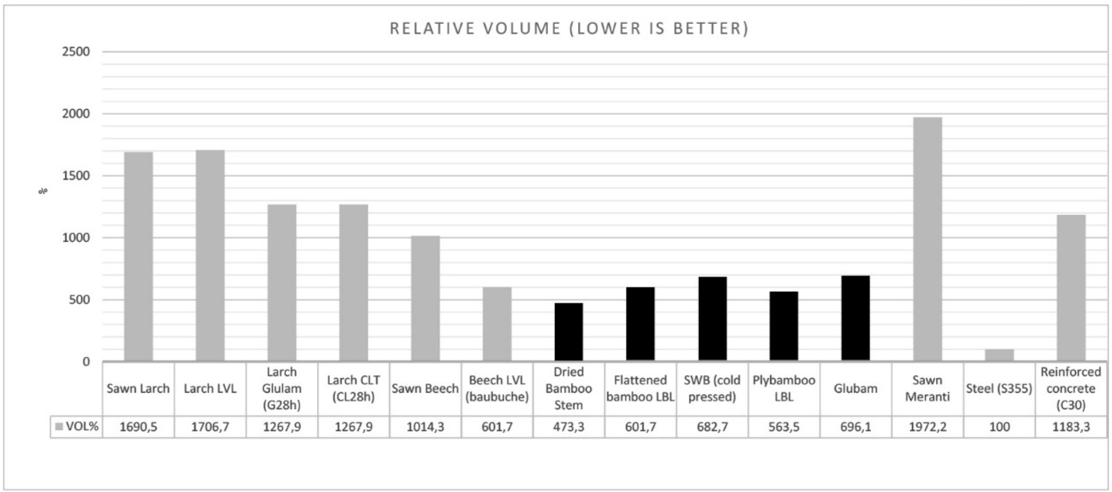


Figure 7: Relative volume comparison. Bamboo outperforms wood- and concrete- based equivalents. Beech LVL also performs significantly well.

Figure 7 shows the relative volume, with respect to s355 steel, of compression elements. It becomes clear that without the added value of height, the bamboo building elements show their full mechanical potential by performing far better than Larch and reinforced concrete building elements. Beech LVL also performs excellently and on par with the bamboo elements. Steel remains the lowest volume option.

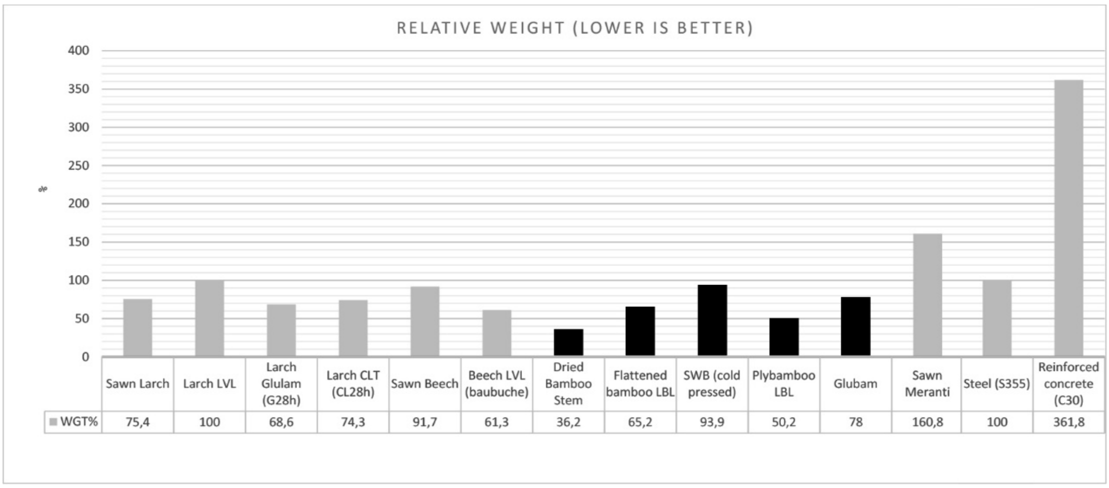


Figure 8: Relative weight comparison. Bamboo-based elements are on par with wood-based elements and better than both steel and concrete.

Figure 8 shows the relative weight, with respect to s355 steel, of compression elements. Both the bamboo-based and the wood-based building elements perform well here, especially when compared to reinforced concrete. Plybamboo LBL performs significantly better than the alternatives, requiring roughly half as much weight as steel. Dried bamboo stems also perform very well, but their application is limited due to afore mentioned geometric constraints.

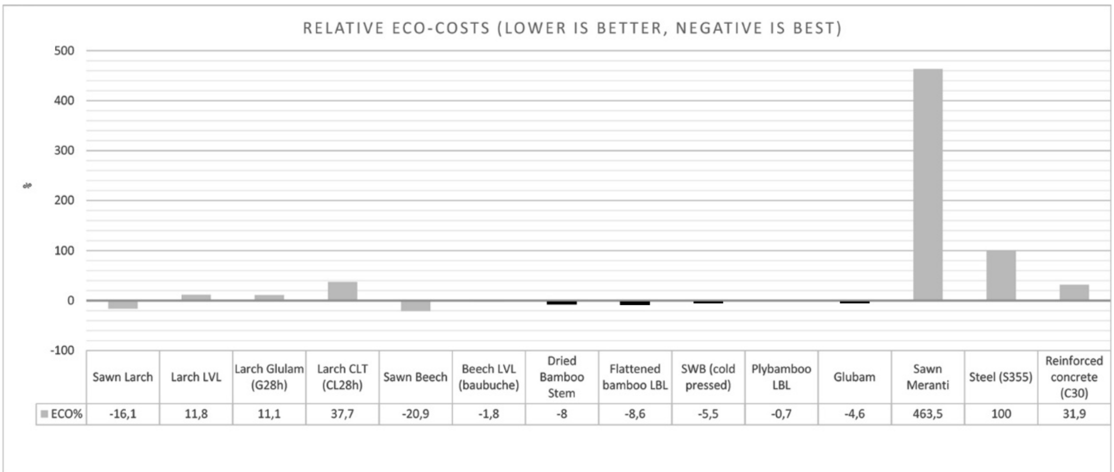
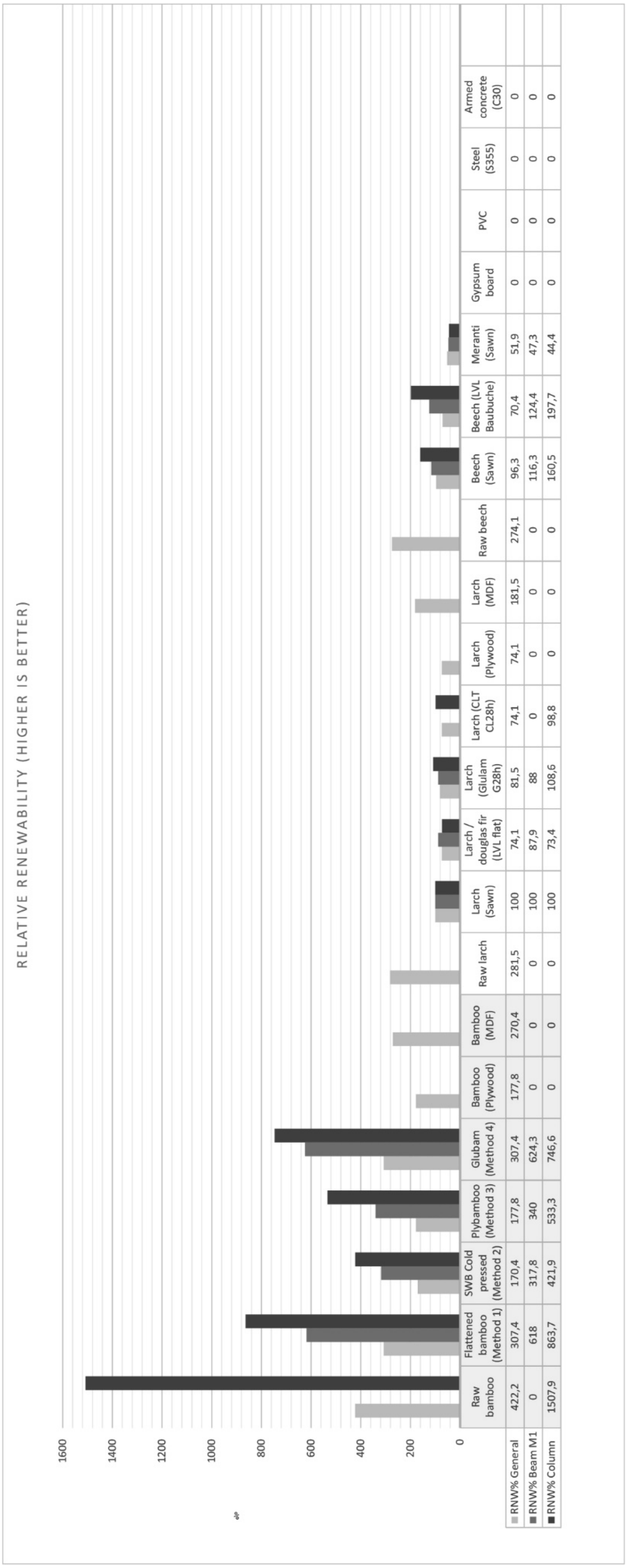


Figure 9: Relative ECO-cost comparison. Bamboo and Beech outperform Larch, steel and concrete. Hardwood performs significantly worse than all alternatives.

Figure 9 shows the relative ECO-cost, with respect to s355 steel, of compression elements. The results are largely in line with earlier results. Noteworthy is the extremely poor performance of hardwood. The poor performance of Larch CLT is also notable, which performs worse than reinforced concrete. The bamboo-based building elements perform well and in line with Beech based elements.

To summarize, bamboo-based compression elements (columns, load bearing walls, stability elements) require less volume than wood-based alternatives and approach steel's performance. With regards to weight, bamboo is comparable to wood-based alternatives and significantly lighter than both concrete and steel. The ECO-cost performance is in line with Beech-based alternatives and better than Larch, steel, concrete and hardwood.

4.1.6. Results Renewability



	Raw bamboo	Flattened bamboo (Method 1)	SWB Cold pressed (Method 2)	Plybamboo (Method 3)	Glubam (Method 4)	Bamboo (Plywood)	Bamboo (MDF)	Raw larch	Larch (Sawn)	Larch / douglas fir (LVL flat)	Larch (Glulam G28h)	Larch (CLT CL28h)	Larch (Plywood)	Larch (MDF)	Raw beech	Beech (Sawn)	Beech (LVL Baubuche)	Meranti (Sawn)	Gypsum board	PVC	Steel (S355)	Armed concrete (C30)
RNW% General	422,2	307,4	170,4	177,8	307,4	177,8	270,4	281,5	100	74,1	81,5	74,1	74,1	181,5	274,1	96,3	70,4	51,9	0	0	0	0
RNW% Beam M1	0	618	317,8	340	624,3	0	0	0	100	87,9	88	0	0	0	0	116,3	124,4	47,3	0	0	0	0
RNW% Column	1507,9	863,7	421,9	533,3	746,6	0	0	0	100	73,4	108,6	98,8	0	0	0	160,5	197,7	44,4	0	0	0	0

Figure 10: Relative renewability comparison

Figure 10 shows the relative renewability in general and of bending (method 1) and compression elements.

It becomes evident that the excellent mechanical performance of bamboo-based building elements, combined with the high annual yield leads to great renewability, with bamboo-based elements being in the range of 3-8 times more renewable than Larch- and Beech-based elements, depending on use-case.

The good renewability of Beech in relation to Larch is also noteworthy. From this and earlier results, it appears that Beech can also be a great alternative to Larch in almost all cases.

4.2. Finishings

4.2.1. Methodology

The methodology for comparing finishing materials is less quantitative and more qualitative. This is because they are often selected either because they possess certain intrinsic qualities like acoustic damping, or because their aesthetic suits the use case. In order to compare finishing materials, a table is made to compare both quantitative aspects like fire-class, formaldehyde emission, eco-costs and renewability, as well as more qualitative aspects like possible use-cases and acoustic performance.

4.2.2. Source Data

See Appendix 1

4.2.3. Results

Finishing type	Flooring (Indoor)	Flooring (outdoor)	Wall/ceiling coverings (Indoor)	Windowframe	Sheer wall structure	Accoustic performance	Fire Class	Hardness (Brinell)	Formaldehyde emisson	ECO costs/kg	Renewability (m3/yr)
Flattened bamboo	no	no	yes	no	yes	excellent	D	3	E1	-0,09	8,3
SWB (cold pressed)	yes	yes	yes	yes	yes	good	C	9,5	E1	-0,04	4,6
SWB (hot pressed)	yes	yes	yes	yes	yes	good	B	9,5	E1	-0,02	4,6
Plybamboo	yes	no	yes	no	yes	excellent	D	4	E1	-0,01	4,8
Bamboo MDF	no	no	yes	no	no	poor	D	5,4	E1	-0,04	7,3
Sawn Larch	no	no	yes	no	yes	poor	D	2,3	E1	-0,145	2,7
Sawn Meranti	yes	yes	yes	yes	yes	poor	D	4,5	E1	1,36	1,4
HDF Laminate	yes	no	no	no	no	poor	C	5,1	E1	-0,155	4,9
MDF (basic)	no	no	yes	no	no	poor	D	4,7	E1	-0,555	4,9
MDF (fire-resistant)	no	no	yes	no	no	poor	B	4,7	E1	0,145	4,9
OSB	no	no	yes	no	no	poor	D	-	E1	0,03	4,9
Plywood	no	no	yes	no	no	poor	D	6,1	E1	0,095	2
Gypsum fiber (fermacell)	no	no	yes	no	no	excellent	A	30	E1	0,08	0
PVC	yes	yes	no	yes	no	poor	B	20	E1	14,2	0
Aluminium	no	no	yes	yes	yes	poor	B	95	E1	3,16	0
Steel	no	no	no	yes	yes	poor	A	120	E1	0,62	0

Table 3: Finishing elements comparison

Flattened bamboo, Plybamboo and Bamboo LDF/MDF are very comparable to their wooden counterparts. The bamboo products, however, can be cheaper, more renewable and possess better acoustic dampening qualities. This makes them a viable alternative, although they are equally limited in terms of fire safety. Impregnation with fire-resistant substances would still be required, whereas something like gypsum fiber (Fermacell) does not require impregnation. Of the bamboo products, LDF and MDF are good for low-performance use-cases like wall coverings. Flattened bamboo is the most economic and most sustainable option for elements that experience more wear such as floors.

It must be noted that the use of bamboo enables building constructions that further implement its inherent qualities. For example, if a Plybamboo CLB element is used, it requires no additional surface finishing or acoustic insulation. This greatly simplifies the building process, saving time and cost and making it more easily demountable in the future.

Elements that experience more moisture variation or that are exposed to rain, such as windowframes, require a more durable material. Often materials like Meranti hardwood, aluminum or PVC are used. Hot pressed SWB is a great sustainable alternative, although it is more costly than aluminum and PVC. SWB window frames also possess good acoustic properties, unlike hardwood. That said, integration of thermal insulation or very slim dimensioning can be better achieved with aluminum. The optimal material to use as a window frame therefore greatly depends on the situation.

V. DESIGN TOOL

The results from chapter IV are relevant for the academic discussion, and in addition they have implications for designers. To make the use of bamboo building elements more accessible and bridge the gap between theory and practice, a design tool was created.

The goal of the design tool is to assist designers in implementing renewable building materials into their designs by providing them with relevant information, comparisons and conversion charts. It is meant to be used in an early stage of the design process to help the designer make choices with regards to material and building system and see the implications of those choices. It is not to be used for full engineering calculations due to a potential lack of accuracy.
The designer will be guided through the document step-by-step and be asked a series of questions. These questions regard the type of project they are working on, as well as the scale and building method. The tool will then suggest suitable building elements to use. Additionally, it contains visual representations of the different building elements.

For the design tool, along with a full explanation of how to use it, see *Appendix 2*

VI. CONCLUSION

The main research question was as follows:

Can Europe-produced Moso bamboo be optimally engineered into industrialized building elements for use within common typologies and is it a viable alternative to other renewable building materials?

Firstly, it must be noted that Europe-produced Moso bamboo possesses similar properties as Asia-produced Moso bamboo. The same methods of production apply and as such, the same products can be made. There are a number of engineered bamboo variants that can be used to create building elements on an industrial scale, each possessing certain advantages and disadvantages.

Secondly it can be concluded that the Moso bamboo-based building elements presented in this study perform excellently when compared to commonly used European wood-based building elements such as Larch and Beech. In general it can be concluded that for an equally performing building element, bamboo requires less volume, is more cost-effective and far more renewable than common wood-based equivalents. Provided Europe produced Moso bamboo is used, the ECO-cost performance is also on par or better. When Asia produced Moso bamboo is used, the ECO-cost performance is on par with that of European Larch, which is still good (Van der Lugt & Otten, 2006).

The answer to the main research question is therefore as follows: Europe produced Moso bamboo can be engineered into a number of forms, all of which possess a unique quality that makes it well-suited for a particular application. These exact forms of engineered bamboos are currently already being mass produced in Asia and, provided European bamboo growth steadily increases, there is great potential for production of bamboo-based building elements on an industrial scale in Europe.
The unrivaled renewability, relatively low cost and excellent mechanical performance of Moso bamboo building elements give it a significant advantage over other renewable and non-renewable building materials. As such, large-scale application within European typologies appears viable. It must be noted, however, that the growth of Moso bamboo cannot take place in cold and dry conditions. In terms of land-use, therefore, it rarely competes with Larch or Beech. In Europe it should therefore not be seen as a replacement or competitor, but rather as an alternative, especially in high-performance use-cases, such as high-rise applications.

VII. DISCUSSION

Although the application of Moso-bamboo building elements appears viable, there are still a number of notable issues and developments, into which more research would be of value.

Firstly, a issue with regards to the sustainability of engineered bamboo is the resin used for the production. Currently many of the resins used are formaldehyde based, whose production requires petroleum and causes harmful waste products. The application of cellulose-based resins appear to be a promising alternative (Ferdosian et. al. 2016). As this is non-toxic and can be made from bamboo pulp, this would also increase overall product yield. Further research into the application of cellulose-based resins in engineered bamboo products would therefore be useful.

Secondly, there is a growing development of extremely high-performance building elements that combine a natural material like wood with a synthetic material such as glass-fiber. These materials show great mechanical potential with performance that is on par or even better than that of S355 steel. Although the renewability and ECO-cost performance is negatively affected by the synthetic material used, these elements may prove a more sustainable alternative in situations where currently only steel suffices. Research into bamboo/synthetic hybrid materials is currently very limited and still very much in a theoretical stage. This topic warrants further research.

Thirdly, it could be argued that, based on the potential for use in construction, the large-scale growth of Moso bamboo in Europe should be stimulated. High nitrogen and carbon sequestration make bamboo forests particularly interesting with regards to current European climate goals and the consistently high annual yield makes managing a bamboo forest an interesting proposition for farmers. This would have implications on land-use and economy. Further research into the implications of large scale Moso bamboo growth in Europe could boost such developments.

VIII. ACADEMIC REFLECTION

The aim of this paper was to bridge the gap between theory and practice regarding Moso bamboo building elements, using a combination of literature analysis along with a comparative study. The results of this study were then converted into a practical design tool.

The literature analysis, although not presenting any new knowledge, was used to create a more coherent overview of the academic knowledge base. Having this background knowledge about the material helped explain certain characteristics that were found in the comparative study and was a useful addition.

The comparative study resulted in a number of new conclusions that are relevant in the current academic discussion. The results not only add to the existing knowledge base, but also help position bamboo in relation to other materials.

The design tool is essentially a more applied conclusion of the comparative study. As a designer myself, the tool would be of value to me, because it presents differences between materials in a very accessible way. As such, it can be used very early in the design process and take much of the guess work, commonly associated with using experimental materials, away.

All in all, the applied methodology proved to be a good combination. The comparative study could have been conducted separately, but without the theoretical background, the results would not have been coherent, which would have severely reduced the quality of the design tool.

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Appendix 1.1: Raw Data & Source List (Page 1 of 4)

Product	Youngs modulus (GPa)	Source	Bending strength (MPa)	Source	Compression strength (MPa)	Source	ECO-costs / kg	Source	Renewability (m3/ha/yr)	Source	Fire Class	Source	Brinell Hardness	Source	Formaldehyde emisson	Source
Raw larch	-	-	-		-	-	-	-	7,6	Bergstedt & Lyck, 2007	-	-	-	-	E1	*No Formaldehydes used*
Larch (Sawn)	11	Centrum Hout, 2017	24	Centrum Hout, 2017	21	Centrum Hout, 2017	-0,145	Aiming Better, 2019	2,7	Bergstedt & Lyck, 2007; *Own caclulation based on Van der Lugt & Vogtländer, 2014*	D	Centrum Hout, 2019	2,3	Sydor et. al., 2020	E1	*No Formaldehydes used*
Larch / douglas fir (LVL flat)	9	Chai & Ross, 2010	33,8	Chai & Ross, 2010	20,8	Chai & Ross, 2010	0,08	Aiming Better, 2019	2	Bergstedt & Lyck, 2007; *Own caclulation based on Van der Lugt & Vogtländer, 2014*	D	Centrum Hout, 2019	-	-	-	-
Larch (Glulam G28h)	12,6	Centrum Hout, 2017	28	Centrum Hout, 2017	28	Centrum Hout, 2017	0,11	Aiming Better, 2019	2,2	Bergstedt & Lyck, 2007; *Own caclulation based on Van der Lugt & Vogtländer, 2014*	D	Centrum Hout, 2019	-	-	-	-
Larch (CLT CL28h)	-	-	28	Schickhofer et. al., 2016	28	Schickhofer et. al., 2016	0,345	Aiming Better, 2019	2	Bergstedt & Lyck, 2007; *Own caclulation based on Van der Lugt & Vogtländer, 2014*	D	Centrum Hout, 2019	-	-	-	-
Larch (Plywood)	-	-	-	-	-	-	0,095	Aiming Better, 2019	2	Bergstedt & Lyck, 2007; *Own caclulation based on Van der Lugt & Vogtländer, 2014*	D	Centrum Hout, 2019	6,1	Sydor et. al., 2020	E1	*Estimation based on Decopanel, 2020*
Larch (MDF)	-	-	-	-	-	-	-0,555	Aiming Better, 2019	4,9	Bergstedt & Lyck, 2007; *Own caclulation based on Van der Lugt & Vogtländer, 2014*	D	Decopanel, 2020	4,7	Decopanel, 2020	E1	Decopanel, 2020
Larch (MDF Fire-resistant)	-	-	-	-	-	-	0,145	Aiming Better, 2019	4,9	Bergstedt & Lyck, 2007; *Own caclulation based on Van der Lugt & Vogtländer, 2014*	B	Decopanel, 2020	4,7	Decopanel, 2020	E1	Decopanel, 2020
Larch (HDF)	-	-	-	-	-	-	-0,155	Aiming Better, 2019	4,9	Bergstedt & Lyck, 2007; *Own caclulation based on Van der Lugt & Vogtländer, 2014*	C	Fritz EGGER GmbH & Co. OG Holzwerkstoffe, 2015	5,1	Fritz EGGER GmbH & Co. OG Holzwerkstoffe, 2015	E1	Fritz EGGER GmbH & Co. OG Holzwerkstoffe, 2015
Larch (OSB4)	-	-	28	Centrum Hout, 2017	-	-	0,03	Aiming Better, 2019	4,9	Bergstedt & Lyck, 2007; *Own caclulation based on Van der Lugt & Vogtländer, 2014*	D	Centrum Hout, 2019	-	-	E1	*Estimation based on Decopanel, 2020*
Larch LVL/OSB4 hybrid HEM-profile	-	-	33,5	*Calculated*	-	-	0,07	Aiming Better, 2019 + *Own calculation*	3,04	Bergstedt & Lyck, 2007; *Own caclulation based on Van der Lugt & Vogtländer, 2014*	D	*Estimation based on Centrum Hout, 2019*	-	-	-	-
Raw beech	-	-	-	-	-	-	-	-	7,4	Myklush, 2010	-	-	-	-	E1	*No Formaldehydes used*

Appendix 1.2: Raw Data & Source List (Page 2 of 4)

Product	Youngs modulus (GPa)	Source	Bending strength (MPa)	Source	Compression strength (MPa)	Source	ECO-costs / kg	Source	Renewability (m3/ha/yr)	Source	Fire Class	Source	Brinell Hardness	Source	Formaldehyde emisson	Source
Beech (Sawn)	14,2	Centrum Hout, 2017	35	Centrum Hout, 2017	35	Centrum Hout, 2017	-0,155	Aiming Better, 2019	2,6	Myklush, 2010; *Own caclulation based on Van der Lugt & Vogtländer, 2014*	D	Centrum Hout, 2019	-	-	E1	*No Formaldehydes used*
Beech (LVL Baubuche)	15,3		75	Pollmeier, 2018	59	Pollmeier, 2018	-0,02	Aiming Better, 2019	1,9	Myklush, 2010; *Own caclulation based on Van der Lugt & Vogtländer, 2014*	D	Centrum Hout, 2019	-	-	-	-
Beech LVL/OSB4 hybrid HEM-profile	-	-	72,2	*Calculated*	-	-	-0,01	Aiming Better, 2019 + *Own calculation*	2,4	Myklush, 2010; *Own caclulation based on Van der Lugt & Vogtländer, 2014*	D	*Estimation based on Centrum Hout, 2019*	-	-	-	-
Beech LVL/LVL hybrid HEM-profile	-	-	72,5	*Calculated*	-	-	0	Aiming Better, 2019 + *Own calculation*	1,92	Myklush, 2010; *Own caclulation based on Van der Lugt & Vogtländer, 2014*	D	*Estimation based on Centrum Hout, 2019*	-	-	-	-
Raw bamboo	9	Chung & Yu, 2002	50	Chung & Yu, 2002	75	Chung & Yu, 2002	-0,15	Van der Lugt & Vogtländer, 2014 + *Own calculation*	11,4	Van der Lugt & Vogtländer, 2014	-	-	-	-	E1	*No Formaldehydes used*
Flattened bamboo (Method 1)	8,4	Mahdavi et. al., 2011	97	Mahdavi et. al., 2011	59	Mahdavi et. al., 2011	-0,09	Van der Lugt & Vogtländer, 2014 + *Own calculation*	8,3	Van der Lugt & Vogtländer, 2014	D	MOSO®, 2020	3	MOSO®, 2020	E1	MOSO®, 2020
SWB Cold pressed (Method 2)	10,9	Mahdavi et. al., 2011	83,5	Mahdavi et. al., 2011	52	Mahdavi et. al., 2011	-0,04	Van der Lugt & Vogtländer, 2014 + *Own calculation*	4,6	Van der Lugt & Vogtländer, 2014	C / B	MOSO®, 2020	9,5	MOSO®, 2020	E1	MOSO®, 2020
Plybamboo (Method 3)	9,8	Sinha et. al., 2013	87,8	Sinha et. al., 2013	63	Sinha et. al., 2013	-0,01	Van der Lugt & Vogtländer, 2014 + *Own calculation*	4,8	Van der Lugt & Vogtländer, 2014	D	MOSO®, 2020	4	MOSO®, 2020	E1	MOSO®, 2020
Glubam (Method 4)	10,4	Xiao et. Al., 2013;2020	99	Xiao et. Al., 2013;2020	63	Xiao et. Al., 2013;2020	-0,04	Van der Lugt & Vogtländer, 2014 + *Own calculation*	8,3	*Own calculation based on Van der Lugt & Vogtländer, 2014*	D	MOSO®, 2020	3	MOSO®, 2020	E1	MOSO®, 2020
Bamboo (Plywood)	-	-	-	-	-	-	-0,01	Van der Lugt & Vogtländer, 2014 + *Own calculation*	4,8	Van der Lugt & Vogtländer, 2014	D	MOSO®, 2020	4	MOSO®, 2020	E1	MOSO®, 2020
Bamboo (MDF)	-	-	-	-	-	-	-0,04	Van der Lugt & Vogtländer, 2014 + *Own calculation*	7,3	*Own calculation based on Van der Lugt & Vogtländer, 2014*	D	*Estimation based on MOSO®, 2020*	5,4	*Estimation based on MOSO®, 2020*	E1	*Estimation based on MOSO®, 2020*
Flattened Bamboo LBL/OSB4 hybrid HEM-profile	-	-	93,6	*Calculated*	-	-	-0,07	Van der Lugt & Vogtländer, 2014 + *Own calculation*	7,53	*Own calculation based on Van der Lugt & Vogtländer, 2014*	D	*Estimation based on MOSO®, 2020*	-	-	E1	-
Flattened Bamboo LBL/LVL hybrid HEM-profile	-	-	93,3	*Calculated*	-	-	-0,06	Van der Lugt & Vogtländer, 2014 + *Own calculation*	7,05	*Own calculation based on Van der Lugt & Vogtländer, 2014*	D	*Estimation based on MOSO®, 2020*	-	-	E1	-
Glubam/OSB4 hybrid HEM-profile	-	-	94,8	*Calculated*	-	-	-0,03	Van der Lugt & Vogtländer, 2014 + *Own calculation*	7,52	*Own calculation based on Van der Lugt & Vogtländer, 2014*	D	*Estimation based on MOSO®, 2020*	-	-	E1	-
Glubam/LVL hybrid HEM-profile	-	-	95,2	*Calculated*	-	-	-0,02	Van der Lugt & Vogtländer, 2014 + *Own calculation*	7,05	*Own calculation based on Van der Lugt & Vogtländer, 2014*	D	*Estimation based on MOSO®, 2020*	-	-	E1	-
Meranti (Sawn)	10,5	Centrum Hout, 2017	20	Centrum Hout, 2017	18	Centrum Hout, 2017	1,96	Aiming Better, 2019	1,4	Brown, 2000	D	Centrum Hout, 2019	4,5	Sydor et. al., 2020	E1	*No Formaldehydes used*

Appendix 1.3: Raw Data & Source List (Page 3 of 4)

Product	Youngs modulus (GPa)	Source	Bending strength (MPa)	Source	Compression strength (MPa)	Source	ECO-costs / kg	Source	Renewability (m3/ha/yr)	Source	Fire Class	Source	Brinell Hardness	Source	Formaldehyde emisson	Source
Gypsum board	-	-	-	-	-	-	0,08	Aiming Better, 2019	-	-	A	Fermacell BV, 2019	30	Fermacell BV, 2019	E1	Fermacell BV, 2019
PVC	3,2	Joostdevree, n.d.	85	Naeff nv, n.d.	85	Naeff nv, n.d.	14,2	Aiming Better, 2019	-	-	B	IVF, 2014; Unifloor Underlay Systems BV, 2014	20	Unifloor Underlay Systems BV, 2014	E1	Unifloor Underlay Systems BV, 2014
Steel (S355)	210	Joostdevree, n.d.	355	MCB Nederland, n.d.	355	MCB Nederland, n.d.	0,68	Aiming Better, 2019	-	-	A	IVF, 2014	120	Tabor, 2000	E1	*No Formaldehydes used*
Aluminium	-	-	-	-	-	-	3,16	Aiming Better, 2019	-	-	B	IVF, 2014	95	Tabor, 2000	E1	*No Formaldehydes used*
Reinforced concrete (C30)	40	Joostdevree, n.d.	30	BetonLexicon, 2018	30	BetonLexicon, 2018	0,06	Aiming Better, 2019	-	-	A	IVF, 2014	-	-	E1	*No Formaldehydes used*

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Appendix 1.4: Raw Data & Source List (Page 4 of 4)

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Appendix 2.1: Design Tool (Page 1 of 12)

Introduction
This design tool was created to assist designers in implementing renewable building materials into their designs by providing them with relevant information, comparisons and conversion charts. It is meant to be used in an early stage of the design process to help the designer make choices with regards to material and building system and see the implications of those choices. It is not to be used for full engineering calculations due to a potential lack of accuracy.

How it works
You will be guided through the document step-by-step and be asked a series of questions. These questions regard the type of project you are working on, as well as the scale and building method. The tool will then suggest suitable building elements to use.

For each building element, there will be three options: the most balanced option, the most sustainable option and the most cost-effective option. When there is no difference between options, they will be merged into one option. Feel free to make your own choice, depending on your priorities.

Upon selecting a building element, you will be referred to a conversion chart. The conversion charts project the data of researched renewable building elements against the data of steel building elements. It was set up so that you can use the common rules of thumb for steel and easily convert them into different materials that perform equally.

Option elaboration
The best balance option contains the best overall balance of characteristics that are relevant for the project scale and construction method. The most sustainable option is a suitable element with the best ECO-cost performance and/or best relative renewability. The most cost-effective option is the most cost-effective, either due to low material cost, fast construction speed or both. The most lightweight option is a suitable element with the lowest relative weight. This option can be especially useful when building on top of an existing building, for example.

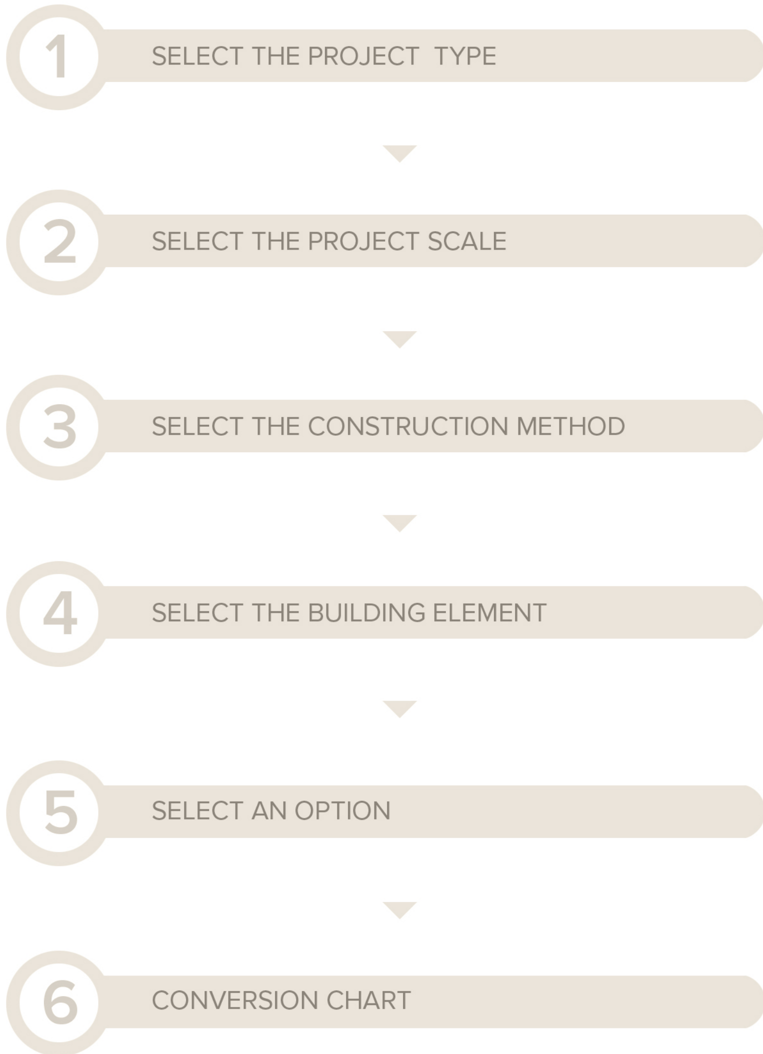
Example scenario
I am a designer working on a small house and have decided that I want to make the house as sustainable as possible, but the budget is limited.
I select new-build, because it is a new-build project. The density is low, so I select low-density. I am now presented with the choice of whether I want to use a skeletal building system or a disk building system. The client wants large windows on all sides of the house, so I choose skeletal.

Upon working on the floor-plan, I am interested in the dimensioning of the columns. I see that the most sustainable choice is a sawn Beech column. However, because the budget is limited and I want the columns to be on the slim side, I select the most cost-effective option, which is a Flattened bamboo LBL column.
The design tool refers me to Table 1. Here I can quickly see that the column I have selected needs roughly 6 times the area of a steel column, weights rougly 0,6 as much as a steel column and has roughly 11 times better eco-cost performance.

I use a simple calculation and my steel profile app to determine that a SHS-HF 60x60x5 with an area of 1073mm2 is needed. With the data from the tool I can quickly calculate that my Flattened bamboo LBL column needs to be 6438mm2. I take the square root of this to find that the column needs to be a square 80x80mm profile.

I now continue designing with the knowledge that I have selected the most sustainable column for my budget. Additionally, I can prove this to my client using the ECO-cost comparion.

Extra note
Options for facades are exempt from this tool due to the large regional variation in technical requirements. Additionally, facade materials are often largely dependent on the desired architectural expression. Table 5 does, however, also contain data relevant for facades.



Appendix 2.2: Design Tool (Page 2 of 12)

1 SELECT THE PROJECT TYPE

NEW-BUILD OR RENOVATION

CHOOSE OWN PRIORITY

ADDITION

PRIORITIZE LOW-WEIGHT OPTION

2 SELECT THE PROJECT SCALE

LOW-DENSITY

CONTINUE ON PAGE 3

MEDIUM- TO HIGH-DENSITY

CONTINUE ON PAGE 5

EXTREME-DENSITY

CONTINUE ON PAGE 7

Appendix 2.3: Design Tool (Page 3 of 12)

LOW DENSITY

3 SKELETAL CONSTRUCTION

Priority on low costs, sound-proofing, minimal separator wall volume and lower demands for fire. Emphasis on volume & costs saving

4	5	6	
COLUMN	BEST BALANCE	Plybamboo LBL (square profile)	TABLE 1
	MOST SUSTAINABLE	Sawn Beech (square profile)	
	MOST COST-EFFECTIVE	Flattened bamboo LBL (square profile)	
MAIN BEAM	BEST BALANCE	Glubam (4:1 profile)	TABLE 2
	MOST SUSTAINABLE & COST-EFFECTIVE	Flattened bamboo LBL (4:1 profile)	
FLOOR	BEST OVERALL	Glubam CLB hollow core	TABLE 3
ROOF	BEST BALANCE	Flattened bamboo LBL rafters & joists (4:1 profile) Sawn Larch battens (4:1 profile) Finishing of choice	TABLE 2
	MOST SUSTAINABLE	Sawn Beech rafters & joists (4:1 profile) Sawn Beech battens (4:1 profile) Finishing of choice	
	MOST COST-EFFECTIVE	Flattened bamboo LBL rafters & joists (4:1 profile) Flattened bamboo LBL battens (4:1 profile) Finishing of choice	
SEPARATOR WALL	BEST BALANCE & MOST SUSTAINABLE	Flattened bamboo CLB	TABLE 4 & 5
	MOST COST-EFFECTIVE	Sawn Larch framing Rockwool insulation Gypsum fiber board finishing	
STABILITY ELEMENT	BEST BALANCE & MOST SUSTAINABLE	Flattened bamboo LBL CLB	
	MOST COST-EFFECTIVE	Steel tension cross	

Appendix 2.4: Design Tool (Page 4 of 12)

LOW DENSITY

3 DISK CONSTRUCTION

Priority on low costs, sound-proofing, minimal separator wall volume and lower demands for fire. Emphasis on fast construction and easy de-/remountability

4	5	6	
LOAD BEARING WALL	BEST OVERALL	Flattened bamboo LBL CLB	TABLE 4
FLOOR	BEST OVERALL	Glubam CLB hollow core	TABLE 3
ROOF	BEST BALANCE	Flattened bamboo LBL rafters & joists (4:1 profile) Sawn Larch battens (4:1 profile) Finishing of choice	TABLE 1
	MOST SUSTAINABLE	Sawn Beech rafters & joists (4:1 profile) Sawn Beech battens (4:1 profile) Finishing of choice	
	MOST COST-EFFECTIVE	Flattened bamboo LBL rafters & joists (4:1 profile) Flattened bamboo LBL battens (4:1 profile) Finishing of choice	
SEPARATOR WALL	BEST BALANCE & MOST SUSTAINABLE	Flattened bamboo CLB	TABLE 5
	MOST COST-EFFECTIVE	Sawn Larch framing Rockwool insulation Gypsum fiber board finishing	

Appendix 2.5: Design Tool (Page 5 of 12)

MEDIUM / HIGH DENSITY

3 SKELETAL CONSTRUCTION

Priority on fast, low-cost and prefabricated construction. Good sound-proofing, low construction volume and low weight.

4	5	6	
COLUMN	BEST BALANCE & MOST SUSTAINABLE	Plybamboo LBL (square profile)	TABLE 1
	MOST COST-EFFECTIVE	Flattened bamboo LBL (square profile)	
	MOST LIGHTWEIGHT	Plybamboo LBL (square profile)	
MAIN BEAM	BEST OVERALL	Flattened bamboo LBL / OSB4 Hybrid (HEM-profile)	TABLE 2
	MOST LIGHWEIGHT	Larch LVL / OSB4 Hybrid bamboo LBL (HEM-profile)	
FLOOR	BEST BALANCE & MOST SUSTAINABLE	Glubam CLB hollow core	TABLE 3
	MOST COST-EFFECTIVE & MOST LIGHWEIGHT	Flattened bamboo LBL CLB hollow core	
ROOF	BEST BALANCE & MOST SUSTAINABLE	Glubam CLB hollow core	TABLE 3
	MOST COST-EFFECTIVE & MOST LIGHWEIGHT	Flattened bamboo LBL CLB hollow core	
SEPARATOR WALL	BEST BALANCE & MOST SUSTAINABLE	Flattened bamboo CLB Fire-resistant impregnated bamboo MDF	TABLE 4 & 5
	MOST COST-EFFECTIVE & MOST LIGHTWEIGHT	Sawn Larch framing Rockwool insulation Fire-resistant gypsum fiber board finishing	
STABILITY ELEMENT	BEST BALANCE & MOST SUSTAINABLE	Flattened bamboo LBL CLB	
	MOST COST-EFFECTIVE & MOST LIGHTWEIGHT	Steel tension cross	

Appendix 2.6: Design Tool (Page 6 of 12)

MEDIUM / HIGH DENSITY

3 DISK CONSTRUCTION

Priority on fast, low-cost and prefabricated construction. Good sound-proofing and easy demount-/remountability of the building.

4	5	6	
LOAD BEARING WALL	BEST OVERALL	Flattened bamboo LBL CLB	TABLE 1
FLOOR	BEST BALANCE & MOST SUSTAINABLE	Glubam CLB hollow core	TABLE 3
	MOST COST-EFFECTIVE & MOST LIGHTWEIGHT	Flattened bamboo LBL CLB hollow core	
ROOF	BEST BALANCE & MOST SUSTAINABLE	Glubam CLB hollow core	TABLE 3
	MOST COST-EFFECTIVE & MOST LIGHTWEIGHT	Flattened bamboo LBL CLB hollow core	
SEPARATOR WALL	BEST BALANCE & MOST SUSTAINABLE	Flattened bamboo CLB Fire-resistant impregnated bamboo MDF	TABLE 5
	MOST COST-EFFECTIVE	Sawn Larch framing Rockwool insulation Fire-resistant gypsum fiber board finishing	

Appendix 2.7: Design Tool (Page 7 of 12)

EXTREME DENSITY

3 SKELETAL CONSTRUCTION

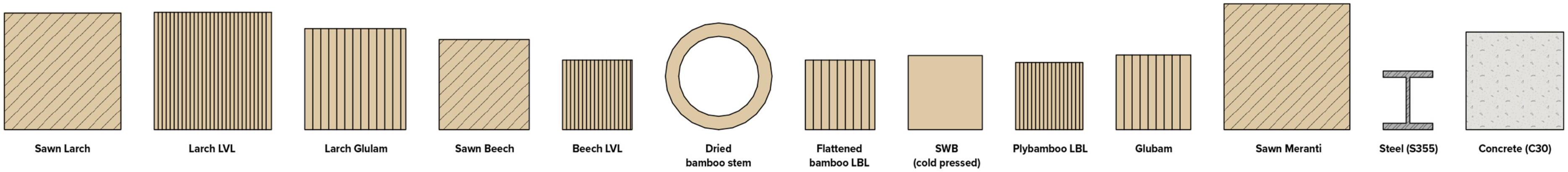
High priority on low-weight , low-volume construction, renewability and demount-/remountability. High priority on sound-proofing, high demands for fire & expandability

4	5	6	
COLUMN	BEST BALANCE & MOST SUSTAINABLE	Plybamboo LBL (square profile)	TABLE 1
	MOST COST-EFFECTIVE	Flattened bamboo LBL (square profile)	
	MOST LIGHTWEIGHT	Plybamboo LBL (square profile)	
MAIN BEAM	BEST OVERALL	Glubam / OSB4 Hybrid (HEM-profile)	TABLE 2
	MOST LIGHWEIGHT	Flattened bamboo LBL / Larch LVL Hybrid (HEM-profile)* Beech LVL (Baubuche) / OSB4 Hybrid (HEM-profile)**	
FLOOR	BEST BALANCE & MOST SUSTAINABLE	Glubam CLB hollow core	TABLE 3
	MOST COST-EFFECTIVE & MOST LIGHWEIGHT	Flattened bamboo LBL CLB hollow core	
ROOF	BEST BALANCE & MOST SUSTAINABLE	Glubam CLB hollow core	TABLE 3
	MOST COST-EFFECTIVE & MOST LIGHWEIGHT	Flattened bamboo LBL CLB hollow core	
SEPARATOR WALL	BEST BALANCE & MOST SUSTAINABLE	Flattened bamboo CLB Fire-resistant impregnated bamboo MDF	TABLE 4 & 5
	MOST COST-EFFECTIVE & MOST LIGHTWEIGHT	Sawn Larch framing Rockwool insulation Fire-resistant gypsum fiber board finishing	
STABILITY ELEMENT	BEST BALANCE & MOST SUSTAINABLE	Flattened bamboo CLB	
	MOST COST-EFFECTIVE & MOST LIGHTWEIGHT	Steel tension cross	

* Best option if less flexural stiffness is required
** Best option if more flexural stiffness is required

Appendix 2.8: Design Tool (Page 8 of 12)

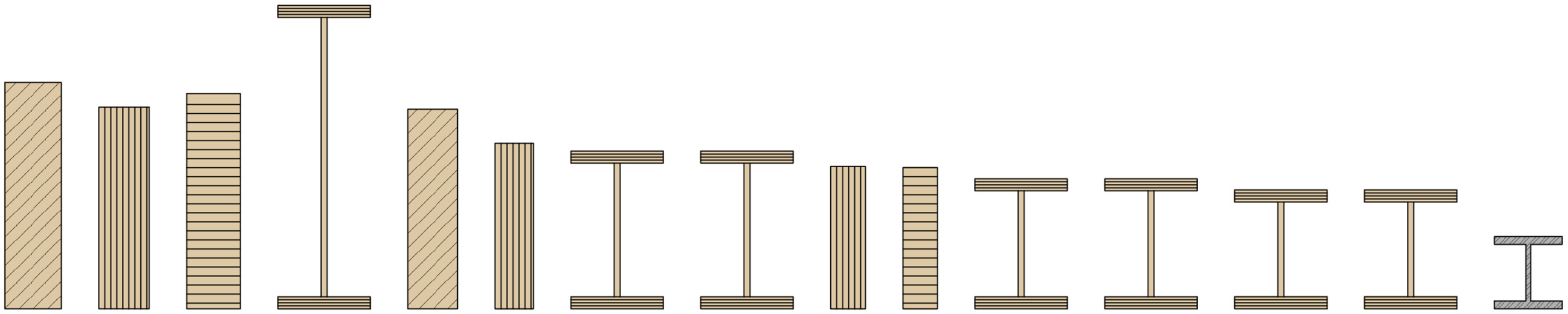
Table 1 - COLUMNS



Column Type	Relative ECO-costs	Relative Volume	Relative Weight	Relative Renewability
Sawn Larch	-0,16	16,91	0,75	1
Larch LVL	0,12	17,07	1	0,73
Larch Glulam (G28h)	0,11	12,68	0,69	1,09
Sawn Beech	-0,21	10,14	0,92	1,61
Beech LVL (baubuche)	-0,02	6,02	0,61	1,98
Dried Bamboo Stem	-0,08	4,73	0,36	15,08
Flattened bamboo LBL	-0,09	6,02	0,65	8,64
SWB (cold pressed)	-0,06	6,83	0,94	4,22
Plybamboo LBL	-0,01	5,64	0,5	5,33
Glubam	-0,05	6,96	0,78	7,47
Sawn Meranti	4,64	19,72	1,61	0,47
Steel (S355)	1	1	1	0
Reinforced concrete (C30)	0,32	11,83	3,62	0

Appendix 2.9: Design Tool (Page 9 of 12)

Table 2 - BEAMS

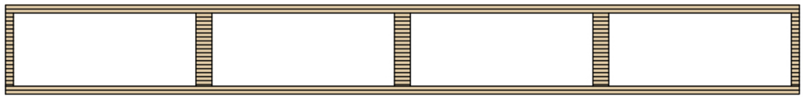


Beam Type	Relative ECO-costs	Relative Volume	Relative Beam Height	Relative Weight	Relative Renewability	Relative W*
Sawn Larch 4:1	-0,09	9,64	3,13	0,43	1	14,79
Larch LVL 4:1	0,05	7,67	2,8	0,45	1,26	10,5
Larch Glulam (GL28h) 4:1	0,08	8,7	2,98	0,47	1,11	12,68
Larch LVL/OSB4 HEM	0,02	3,03	4,2	0,19	3,58	10,6
Sawn Beech 4:1	-0,16	7,5	2,76	0,68	1,24	10,14
Beech LVL (baubuche) 4:1	-0,01	4,51	2,14	0,46	2,06	4,73
Beech LVL (baubuche)/OSB4 Hybrid HEM	0	2,35	2,18	0,23	3,65	4,92
Beech LVL (baubuche)/LVL Hybrid HEM	0	2,35	2,18	0,22	2,92	4,9
Flattened bamboo LBL 4:1	-0,05	3,8	1,97	0,41	7,8	3,66
Glubam 4:1	-0,03	3,75	1,95	0,42	7,91	3,59
Flattened bamboo LBL/OSB4 Hybrid HEM	-0,02	2,22	1,8	0,23	12,1	3,79
Flattened bamboo LBL/LVL Hybrid HEM	-0,02	2,22	1,8	0,22	11,33	3,8
Glubam/OSB4 Hybrid HEM	-0,01	2,17	1,65	0,23	12,36	3,75
Glubam/LVL Hybrid HEM	-0,01	2,17	1,65	0,22	11,58	3,73
Steel (S355) HEM	1	1	1	1	0	1

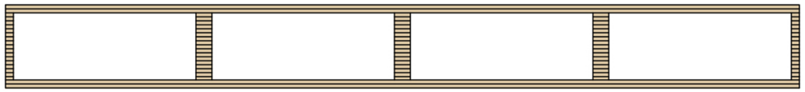
* Use Relative W if a steel W value is known due to a higher degree of accuracy

Appendix 2.10: Design Tool (Page 10 of 12)

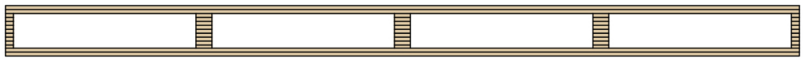
Table 3 - FLOORS



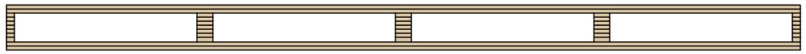
Larch LVL CLT



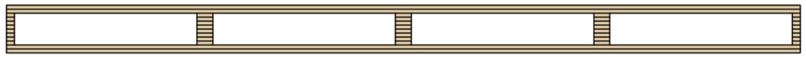
Larch CLT



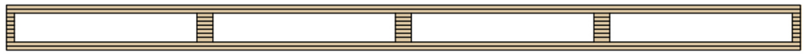
Beech LVL CLT



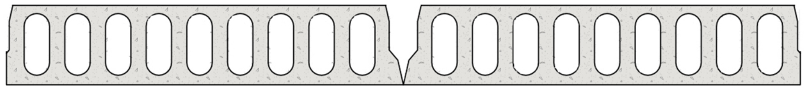
Flattened bamboo LBL CLB



Plybamboo LBL CLB



Glubam CLB

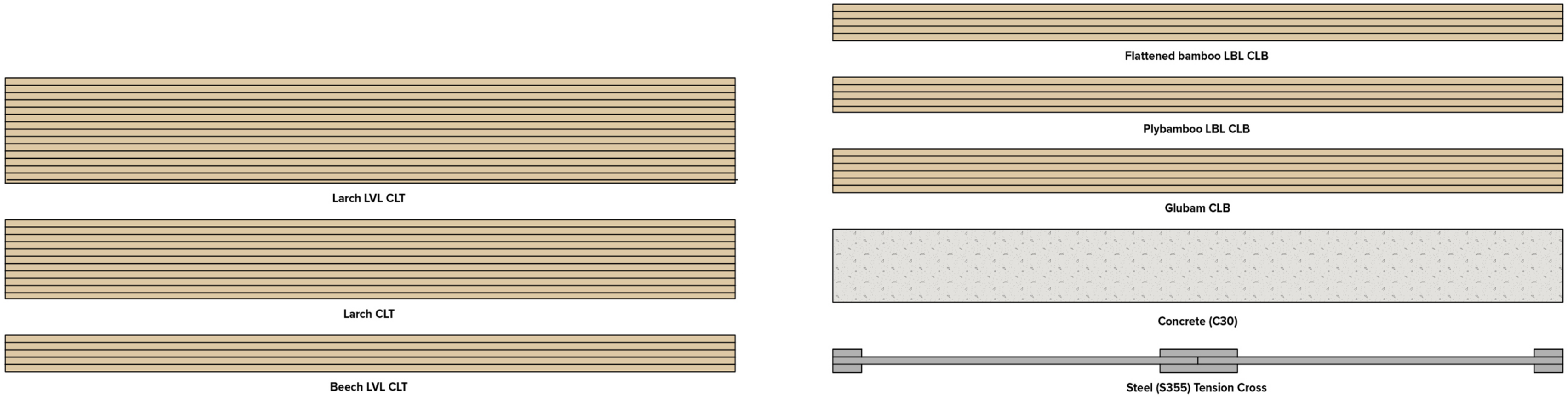


Concrete (C30)

Floor Type	Relative ECO-costs	Relative Volume / Thickness	Relative Weight	Relative Renewability
Larch LVL CLT	0,24	1,12	0,16	1
Larch CLT (CL28h)	0,33	1,04	0,18	1
Beech LVL (baubuche)	-0,08	0,63	0,21	1,41
Flattened bamboo LBL CLB	-0,29	0,56	0,2	7,02
Plybamboo LBL CLB	-0,03	0,59	0,17	3,86
Glubam CLB	-0,13	0,55	0,2	7,09
Reinforced concrete (C30)	1	1	1	0

Appendix 2.11: Design Tool (Page 11 of 12)

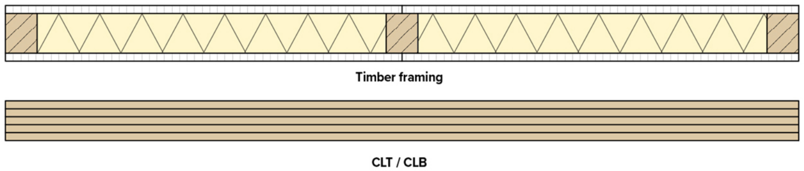
Table 4 - WALLS



Wall type	Relative ECO-costs	Relative Volume / Thickness	Relative Weight	Relative Renewability
Larch LVL CLT	0,37	1,44	0,28	1
Larch CLT (CL28h)	1,18	1,07	0,21	1,48
Beech LVL (baubuche)	-0,06	0,51	0,17	2,69
Flattened bamboo LBL CLB	-0,27	0,51	0,18	11,77
Plybamboo LBL CLB	-0,02	0,48	0,14	7,27
Glubam CLB	-0,14	0,59	0,22	10,17
Reinforced concrete (C30)	1	1	1	0
Steel Tension Cross	-	use seprate guidelines	use seprate guidelines	0

Appendix 2.12: Design Tool (Page 12 of 12)

Table 5 - SEPARATOR WALLS & FINISHING



Finishing type	Flooring (Indoor)	Flooring (outdoor)	Wall/ceiling coverings (Indoor)	Windowframe	Sheer wall structure
Flattened bamboo	no	no	yes	no	yes
SWB (cold pressed)	yes	yes	yes	yes	yes
SWB (hot pressed)	yes	yes	yes	yes	yes
Plybamboo	yes	no	yes	no	yes
Bamboo MDF	no	no	yes	no	no
Sawn Larch	no	no	yes	no	yes
Sawn Meranti	yes	yes	yes	yes	yes
HDF Laminate	yes	no	no	no	no
MDF (basic)	no	no	yes	no	no
MDF (fire-resistant)	no	no	yes	no	no
OSB	no	no	yes	no	no
Plywood	no	no	yes	no	no
Gypsum fiber (fermacell)	no	no	yes	no	no
PVC	yes	yes	no	yes	no
Aluminium	no	no	yes	yes	yes
Steel	no	no	no	yes	yes

Finishing type	Accoustic performance	Fire Class	Hardness (Brinell)	Formaldehyde emisson	ECO costs/kg	Renewability (m3/yr)
Flattened bamboo	excellent	D	3	E1	-0,09	8,3
SWB (cold pressed)	good	C	9,5	E1	-0,04	4,6
SWB (hot pressed)	good	B	9,5	E1	-0,02	4,6
Plybamboo	excellent	D	4	E1	-0,01	4,8
Bamboo MDF	poor	D	5,4	E1	-0,04	7,3
Sawn Larch	poor	D	2,3	E1	-0,145	2,7
Sawn Meranti	poor	D	4,5	E1	1,36	1,4
HDF Laminate	poor	C	5,1	E1	-0,155	4,9
MDF (basic)	poor	D	4,7	E1	-0,555	4,9
MDF (fire-resistant)	poor	B	4,7	E1	0,145	4,9
OSB	poor	D	-	E1	0,03	4,9
Plywood	poor	D	6,1	E1	0,095	2
Gypsum fiber (fermacell)	excellent	A	30	E1	0,08	0
PVC	poor	B	20	E1	14,2	0
Aluminium	poor	B	95	E1	3,16	0
Steel	poor	A	120	E1	0,62	0