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*Article*

# Application of Life Cycle Sustainability Assessment to the bamboo and aluminum bicycles in surveying social risks of developing countries

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**Abstract:** Due to the arising internationally awareness of sustainable development, sustainability has become an ultimate goal for worldwide industries to pursue. To construct a sufficient method for assessing sustainability on the product level nowadays is an important issue but still a challenge. The mature approach, Life Cycle Assessment (LCA), is used to evaluate the environmental burdens. Taking the economic and social dimensions into consideration for a comprehensive life cycle sustainability assessment (LCSA) is necessary and so far in its infancy. Therefore, developing the LCSA is essential and inevitable. To do so, there are two main aims of this study: first, combining LCA, life cycle costing (LCC) and social life cycle assessment (SLCA) on a case study of the bamboo bicycle and the aluminum-frame bicycle, to emphasize on the theoretical development of an overall, scientifically and widely valid method for the integrated sustainability assessment. Second, the study takes the origin of raw materials for bamboo and bauxite from respectively China and Guinea, and bicycle manufacturing in Germany to administer the SLCA practically. The hot spot social life cycle database is used as a starting point for the practical analysis of the social situations of the countries. The study compares environmental impacts between the two bicycles. The overall LCA results indicate that the bamboo bicycle is more environmental advantageous than the aluminum one in many impact categories but not significant except water depletion. If observing only the processes related to frame production, the outcome shows there are significant differences between the two bicycles in specific impact categories such as freshwater eco-toxicity, freshwater eutrophication, marine eco-toxicity and human toxicity; however, while checking the results for the whole life-cycle of the bicycle, the mentioned differences are minor. Besides, this paper adopts LCC fitting best together with LCA boundary as a consistent pillar of sustainability assessment. In LCC, the study focuses on the two perspectives from the manufacturer and the consumer of the two bicycles. On manufacturer perspective, the total cost is to 380.79 € for the bamboo bicycle and 434.55 € for aluminum-frame one; on user perspective, the total cost is 1030.5 € for a bamboo-frame bicycle, significant more than aluminum-frame ones' 728.55 €. While probing social circumstance of developing countries deeply in the SLCA, the results reveal that in China, shortage of labor right, low average wage, and insufficient sanitation in urban area are the main issues. For Guinea, the critical topics are gender equity, child labor, long working time, low wage, lack of labor law and completed legal system, high dropout rate, less improved sanitation, and low living standard.

**Keywords:** Bicycle; Bamboo; Aluminum; Life Cycle Assessment (LCA); Social Life Cycle Assessment (SLCA); Life Cycle Sustainability Assessment (LCSA); China; Germany; Guinea.

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## 1. Introduction

Since the increasing worldwide awareness of sustainable development, sustainability has become an ultimate goal for global governments and industries to pursue. Sustainability includes not only the environmental pillar but the economic and social ones, as defined by the Brundtland commission [1]. To measure sustainability of products and services, constructing an integrated evaluating methodology has become extremely inevitable. Life Cycle Sustainability Assessment (LCSA) has been developed as more comprehensive method to provide the information of three dimensions to stakeholders in recent years. It has been suggested to integrate Life Cycle Assessment (LCA), Environmental Life Cycle Costing (LCC) [2, 3] and Social Life Cycle Assessment (SLCA) [4], formally expressed in the symbolic equation as [5-9]:

$$\text{LCSA} = \text{LCA} + \text{LCC} + \text{SLCA} \tag{1}$$

LCA is an ISO-standardized method [9-11], widely adopted to estimate the potential environmental impacts of products and services through the whole life cycle [9, 12, 13]. It is the most advanced and experienced methodology in probing environmental burden in process or product levels, and also in preventing burden shifting from different life-cycle phases. LCC is proposed for the assessment of the economic dimension of sustainability, and builds further on the traditional life cycle costing which have been used since the 1930s [9, 14]. It is still relatively a new tool in the sustainability assessment [2, 9]. SLCA is a life cycle tool to reflect the social issues of the regions or countries where related to product's life cycle, paying great attention to different topics on stakeholder groups as worker, consumer, local community and society, but still in its infancy with limited research [4, 9].

Bicycling is generally considered as an environmentally friendly way of commuting to reduce environmental impacts [9]. Several studies focused on the life cycle inventory and assessment to make comparison among different transportation types. Leuenberger et al. [15] investigated the life cycle inventory including the infrastructure data of Swiss conventional bicycle, e-bicycle, conventional scooter, and e-scooter with components mainly produced from east Asia. The results found that the manufacturing of the bicycle considerable influenced the LCI results. Moreover, Dave [16] applied hybrid LCA: using an Environmental Input-Output (EIO) LCA approach in manufacturing, assembly and infrastructure stages, and adopting traditional LCA in operation stage of different transportation ways. The study indicated that all forms of personal transport (walking, bicycling, and e-bicycle) are at least three times less of energy input and greenhouse gas emission than any other form of commuter transport (automobiles, bus, rail, and air travel) [16] per passenger-miles-travelled. Blondel et al. [17] even concluded the bicycles' greenhouse gas emissions are over ten times lower than which stemming individual motorized transport while not regarding infrastructure and disposal stages.

However, the previous studies paid high attention only on environmental views of bicycles made from aluminium and steel, considering neither renewable resource as bamboo for bicycle frame production nor economic and social topics. Besides, social issues play an important role in sustainability assessment but haven't been developed further in practical. Many countries which export raw materials are developing countries with adverse social circumstances and low living standard. How to apply SLCA to reflect real social issues of developing countries is a valuable task researchers should investigate further. Therefore, this paper aims to introduce the bamboo bicycle and the aluminium-steel based bicycle as a case study for strengthening LCSA development, and to practice SLCA with surveying developing countries as the origin for bamboo and bauxite from respectively China and Guinea.

## 2. Methods and Data

### *2.1. Overall Goal and Scope of the Study*

The main focus of the study is on using LCA, LCC, and SLCA to evaluate the sustainability in the three dimensions of the bamboo-frame bicycle and the aluminum-frame bicycle manufactured, used, and disposed/recycled Germany. The life cycle system boundaries of the two bicycles in this study are shown in Figure 1. and Figure 2. For each assessment tool, the specific goal, scope and assumptions will be described in corresponding sections. Based on life-cycle thinking, the boundaries of the study mainly include six phases: raw material extraction of frame, raw material processing of frame, manufacturing of other bicycle parts, assembly, use phase, and end of life (EoL). Transports are symbolized by arrows in Figure 1. and Figure 2. To highlight the results of the bicycles from different frames, the raw material extraction and raw material processing stages represent the processes only related to the frame production. The rest components of a bicycle except the frame and tyres are sorted out in "other parts of bicycle." In addition, the raw material extraction of frame for the bamboo frame includes bamboo cultivation and bamboo harvest.

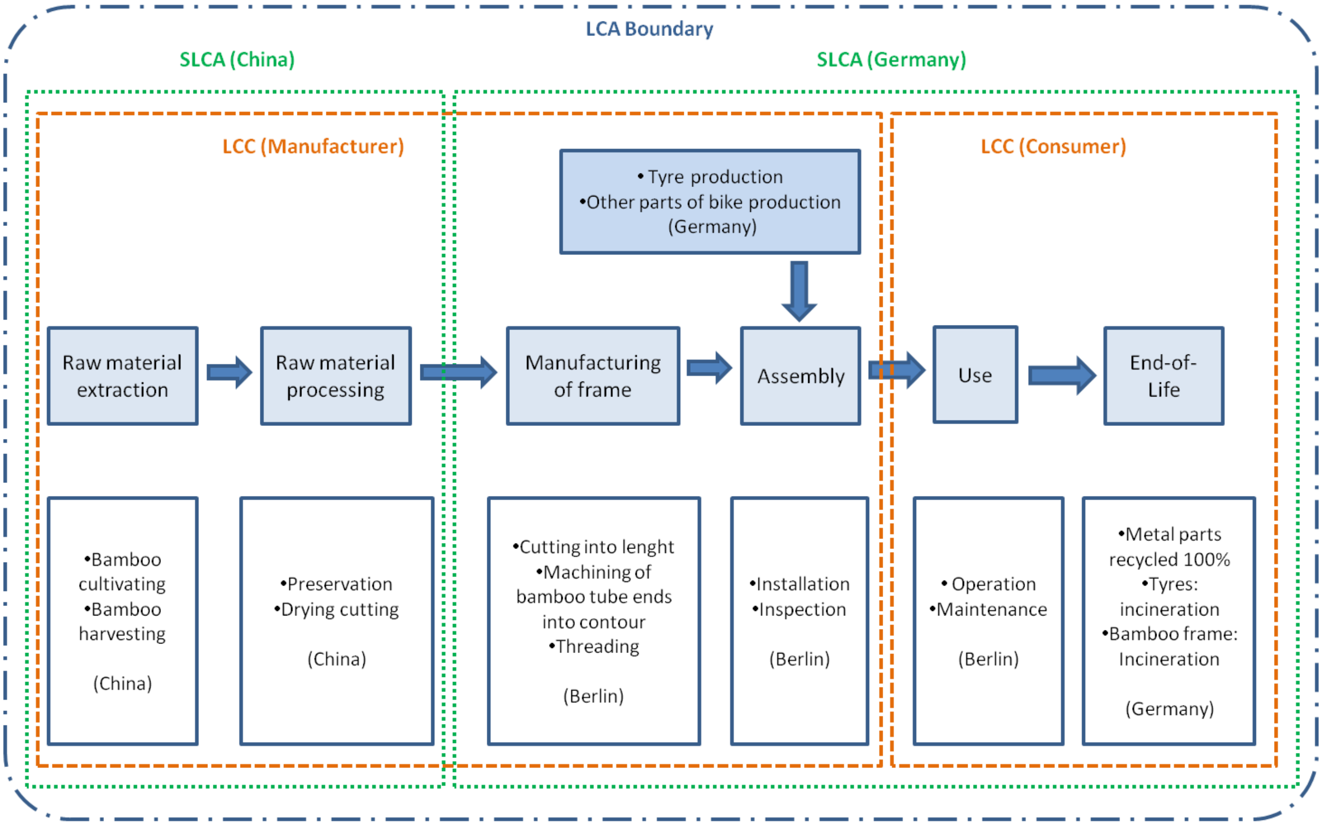


**Figure 1.** System boundaries of the bamboo-frame bicycle [9]

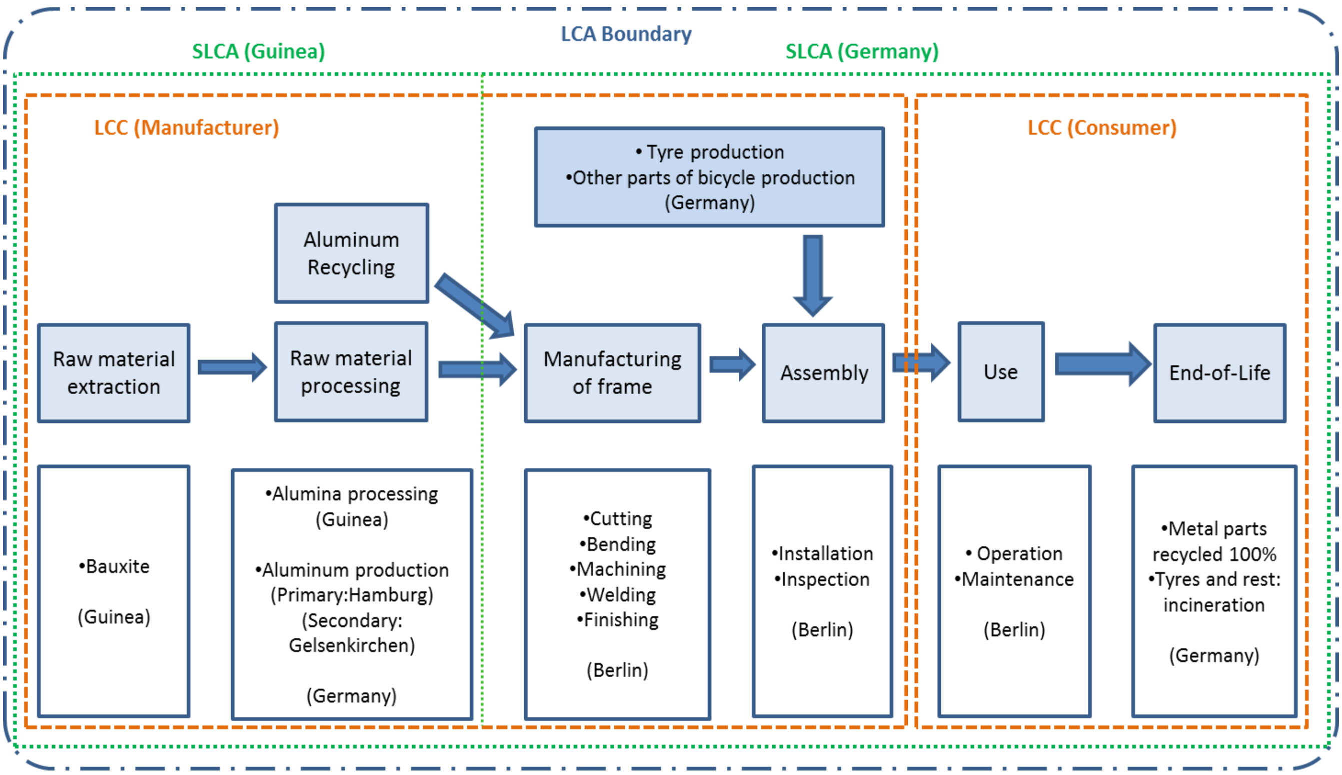


**Figure 2.** System boundaries of the aluminum-frame bicycle [9]

### *2.2. LCA*

LCA structure is divided into the four phases: goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation in an iterative process [9-11]. The goals of this LCA are to:

- highlight the environmental impacts contributed from the different life cycle phases of the bicycle
- compare the differences of environmental impacts between the bamboo-frame bicycle and the aluminium-frame one
- guide the further development of LCA, LCC and SLCA to sustainability assessment tools

The function of the bicycle is to transport one person for commute. The functional unit is 15,000 person kilometers (assuming a daily distance of 10 km for 200 days a year for 7.5 years) which is fulfilled by the reference flow of 1 bicycle. (15,000 km is the life expectancy used for a bicycle in Ecoinvent [15]). In this study, 18 mid-point ReCiPe Indicators are adopted as the life cycle impact assessment indicators [18]; meanwhile, GaBi 4.4 is used as the software to carry out LCA. According to the life cycle systems of the two bicycles shown in Figure 1.and Figure 2., we follow the boundaries and the six main life cycle stages to collect inventory data. The life cycle inventory includes all exchanges or flows e.g. materials and energy between the technosphere (economy) and the nature (environment) crossing the system boundary [12, 23].

#### *2.2.1 Bamboo-frame Bicycle*

At the raw material extraction stage, the considered processes for bamboo-frame bicycle are bamboo cultivation and harvesting from sustainably managed plantations in the Anji region, Zhejiang province, China. Based on literature [19], it is assumed that no pesticides are used on the plantations; on the other hand, manure is adopted as fertilizer in cultivation stage. The reference bamboo is Moso bamboo (*Phyllostachys pubescens*), the most commonly used and industrialized giant bamboo. According to the Moso planting circumstance in Zhejiang province, 3,300 stems per hectare in average [20], we can deduce that the manure usage for per Moso stem is about 34.1 kg [20, 21]. One reference bamboo is 5.33 m stem and will be cut in 2.66 meter long in processing stage [9, 19]. For a bamboo bicycle, the bamboo stem usage is about 3.97 m which weights 2.04 kg [22]. Bamboos are harvested by chainsaw. The corresponding gasoline consumption can be deduced in 0.00427 liters for bamboo stem usage in one bamboo-frame bicycle by adopting bamboo length ratio [19].

Next, in the raw material processing stage, the harvested bamboo stems will be sent to processing plants also in Anji region to have preservation, drying, and cutting into standard lengths. The preservation of bamboo stem is best executed in Boucherie method by an air pump [9, 19]. For 3.97 meter-long bamboo stem, energy usage from an air pump is 2.682 MJ [19]. In the method, the sap will be removed by a boron solution. From the boron solution amount (100 liter water with 12% boron is enough for 480-meter bamboo stem) described in [9, 19], the solution consumption can be calculated to 0.0093 kg for 3.97 meter-long stem. After the preservation process, the remaining solution (sap, water and boron residue) can be reused as fertilizer [9, 19].

After processing, the bamboo stems will be transported from Anji region via Shanghi (China) and Hamburg to Berlin by land and ocean transportation, and then be manufactured further under cutting, matching stem ends, threading by hemp and epoxy, and possible hand-made surface finishing [9]. The amounts of hemp and epoxy are both assumed in 0.1 kg [22]. Tyre production and other parts of bicycle are also included in the manufacturing phase. Based on literatures [15, 22, 23], we can collect the inventory data of tyre (size: 700 x 23) and other parts of bicycle production. The other parts of bicycle includes handlebar, bearing, stem, seat and seat post, wheels, pedals, chain, crankset, brakes, brakehandle, cassett sprockets, derailleurs, shifters, cable, electronic components and other plastics [15]. For tyre production, the factory area is assumed in Reichshof region (taking the Schwalbe Co. for example) [24]; for other parts of bicycle production, the manufacturing region is set as in Berlin.

In the assembly stage, building the bicycle and the final product inspection are the main roles. We assume that workers all assemble the bicycles by hands without energy consumption. Afterwards, during the use stage, operation (commuting between home and office) and maintenance of the bicycles will also be counted for. The emissions from rider's breath are omitted. Tyres are needed to be replaced every 4,000 km for maintenance [9, 15]. In the EoL, this study assumes that all the metal parts can be reused 100%, and the tyres, the rest bicycle parts, and bamboo frame are all incinerated. Assembly, use stage including maintenance, and incineration are all assumed occurring in Berlin region. The total material and energy input during the life cycle for the bamboo bicycles is listed in Table 1., for transport information is shown in Table 2, based on google map calculation and literatures [19, 25-28].

*2.2.2 Aluminum-frame Bicycle*

In the study, to make the clear comparison, we set the assumption that only the production related to frame is different between the two bicycles. The tyre and the other parts of bicycle production in the aluminium-frame bicycle are identical to the bamboo-frame one.

At the raw material extraction phase, the raw material for the aluminum production is bauxite mined in Guinea and processed alumina exported from Guinea to Germany [29]. To reflect the real aluminium production circumstance in Germany, we adopt that in aluminium usage in both bicycles, primary aluminium accounts 40%, and recycled aluminium occupies the rest 60% [30]. In the raw material processing stage, alumina (aluminium hydroxide and aluminium oxide), and liquid primary aluminium processes are considered for primary aluminium production [31]. The main primary aluminium production area is assumed in Hamburg; for recycled aluminium is Gelsenkirchen, Germany [29]. After the processing stage, the primary aluminium and recycled ones are assumed to be sent to Berlin region for producing the frames and components of other parts of bicycle which made from aluminium. The assumptions and circumstance of assembly, use, and EoL stages for the aluminium-frame bicycle are all identical with the bamboo-frame bicycle. The total material and energy input for the aluminum-frame bicycle is also indicated in Table 1., for transport information [9, 19, 25, 26, 28, 32] is expressed in Table 2.

Table 1. Main materials and energy input of the two bicycles [9, 15, 19, 23]

| Item | Bamboo-frame Bicycle | Aluminum-frame Bicycle | Unit |
|---|---|---|---|
| Fertilizer (Manure) | 34.10 | - | kg |
| Gasoline | 0.00427 | - | L |
| Boron solution | 0.93 | - | kg |
| Bamboo stem | 2.04 | - | kg |

| | | | |
|---|---|---|---|
| Hemp | 0.1 | - | kg |
| Epoxy resin | 0.1 | - | kg |
| Bauxite | 8.29 | 12.40 | kg |
| Primary aluminium | 2.02 | 3.02 | kg |
| Secondary aluminium | 3.02 | 4.52 | kg |
| Steel, alloyed | 4.78 | | kg |
| Stainless steel | 1.71 | | kg |
| High density polyethylene (HDPE) | 1.96 | | kg |
| PU, flexible foam | 0.03 | | kg |
| Electronic equipment | 0.5 | | kg |
| Natural rubber (NR) | 794.24 | | g |
| Styrene-butadiene rubber (SBR) | 521.50 | | g |
| Polybutadiene (BR) | 263.52 | | g |
| Butyl rubber (IIR) | 98.76 | | g |
| Carbon black | 867.62 | | g |
| Rubber chemicals (Benzothiadiazole compounds) | 450.89 | | g |
| Bead wire (Polypropylene) | 142.60 | | g |
| Viscose fibre (Rayon) | 190.14 | | g |
| Tap water | 0.602 | 0.711 | kg |
| Energy | 67.74 | 70.81 | MJ |

Table 2. Transportaion of the two bicycles (km) [19, 25-28, 32]

| Transportation step | Site | Transportation Type | Distance |
|---|---|---|---|
| Raw material extraction/processing for the bamboo-frame bicycle | | | |
| Send bamboo stems from plantation area to processing plants | In Anji region, Zhejiang, China | 5-ton truck (empty truck load for return) | 30 |
| Send processed the stems to harbour | Anji-Shanghi, China | 28-ton truck (one way) | 600 |
| Export the stems | Shanghi-Hamburg, Germany | Trans-oceanic freight ship (40-foot container) | 19737 |
| Send the stems for further production | Hamburg-Berlin | 28-ton truck (one way) | 300 |
| Raw material extraction/processing for the aluminium-frame bicycle | | | |
| Export alumina | Guinea-Hamburg | Trans-oceanic freight ship (40-foot container) | 5961.6 |
| For primary aluminium production | In Hamburg region | 28-ton truck (one way) | 20 |

| | | | |
|---|---|---|---|
| Send primary aluminium for further production | Hamburg-Berlin | 28-ton truck (one way) | 300 |
| Send secondary aluminium for further production | Gelsenkirchen-Berlin | 28-ton truck (one way) | 500 |
| Frame production and assembly | | | |
| Bamboo frame/aluminium frame for production/assembly | In Berlin region | 7.5-ton truck (one way) | 20 |
| Tyres for assembly | Reichshof-Berlin | 7.5-ton truck (one way) | 600 |
| Collect the other parts of bike for assembly | In Berlin region | 7.5-ton truck (one way) | 20 |
| Use phase | | | |
| Send bicycles to retailers | In Berlin region | 7.5-ton truck (one way) | 20 |
| Tyres for maintenance | Reichshof-Berlin | 7.5-ton truck (one way) | 600 |
| End-of-Life | | | |
| Incineration and metal collection | In Berlin region | 7.5-ton truck (one way) | 20 |

### *2.3. LCC*

#### *2.3.1 Bamboo Bicycle*

We adopt environmental life cycle costing (LCC) [33] fitting best together with LCA as a consistent pillar of sustainability assessment [9, 34]. LCC by any one or more of the actors in the product life cycle (e.g., supplier, manufacturer, user or consumer, or EoL actor) with complementary inclusion of externalities that are anticipated to be internalized in the decision-relevant future" [9, 33]. This study focuses on the two perspectives: the manufacturers and the consumers of the bamboo bicycle, as the boundary shown in Figure 1. For the manufacturer perspective, the following describes the considered cost categories [9]:

- Acquisition cost for purchasing a bamboo stem, tyres, other bicycle parts and related material input
- Labor cost in assembly stage
- Transportation cost for collecting bamboo stem, tyres, and other bicycle parts to assembly plant, and sending the bicycle to retailers.

The LCC inventory from manufacturer perspective is listed in Table 3. The price of bamboo stems is supposed to cover the cultivation, harvest, and transportation costs in China [35]. The costs of purchasing hemp and epoxy are also taken into account [22, 36]. For tyres and the other bicycle components, we assume the cost is 80% of the retail price from [22, 37] to simulate acquisition cost of manufacturers. For labor involved in assembly, the working time is 32 minutes per bicycle [9, 38] with the German hourly personal costs of 43.76 € [9, 39]. We can deduce the labor cost as 23.34 €. The manufacturer affords transportation costs for collecting the other parts of bicycle and tyres in from the suppliers. Based on statistical coverage of the logistics sector in the EU [40], truck volume and transportation distances [24-26, 28, 40-42], the transportation costs are calculated listed also in Table 3.

In the consumer perspective, the cost includes acquisition cost (purchase price from retailers [38]), maintenance cost (e.g. new tyres every 4,000 km [15]) for 6 tyres of the bicycle in use stage [37], and salvage value, as shown in Table 4. In the case study, due to consumers may turn the used bamboo bicycles back to retailers, we assume the salvage value is 10% of the original purchase price as the discounts for buying new bicycles. Transportation costs are omitted since simplifying the possible different personal behaviour of consumers. Fixed costs such as insurance and tax are omitted to reflect current consumer behaviour [9].

*2.3.2 Aluminum-frame Bicycle*

As same as the calculation of the bamboo bicycle, we focus on the manufacturers and the users perspectives of the aluminium-frame bicycle in the identical categories. For manufacturer perspective, the costs considered are [9]:

- Acquisition cost for purchasing an aluminium frame, tyres, other bicycle parts
- Labor cost in assembly stage
- Transportation cost for collecting an aluminium frame, tyres, and other bicycle parts to assembly plant, and sending the bicycle to retailers.

The price of an aluminium frame in average [43] is assumed to cover the bauxite extraction, processing, and transportation costs from Guinea to Hamburg. The prices for purchasing tyres and the other bicycle components, and the labor cost are the same as the estimation from the bamboo-frame bicycle. In transportation cost, adopting the distances shown in Table 2., we can deduce the costs for the bicycle manufacturer to collect aluminium frame, tyres and other bicycle parts, and to send the bicycles to retailers in Berlin region [24-26, 28, 32, 40-42].

In consumer perspective, acquisition cost [44, 45], maintenance cost for 6 tyres [9, 15, 37], and salvage value (10% of original bicycle purchase price) are considered. Based on the identical assumption with bamboo-frame bicycle, the transportation cost and fixed costs are also omitted. The total LCCs of the two perspectives are expressed in Table 3. and Table 4.

Table 3. The LCC in manufacturer perspective (Euro) [9, 43]

| Item | Bamboo-frame bicycle | Aluminum-frame bicycle |
|---|---|---|
| Acquisition cost | | |
| Bamboo stems | 3.59 | - |
| Epoxy resin | 2.53 | - |
| Hemp fiber | 2.11 | - |
| Aluminum frame | - | 62 |
| Tyres | 48 | 48 |
| Other parts of bike | 299.43 | 299.43 |
| Subtotal | 355.66 | 409.43 |
| Labor cost | | |
| Labor involved in assembly | 23.34 | 23.34 |
| Transportation cost | | |
| Components to assembling plant | 0.09 | 0.09 |

| | | |
|---|---|---|
| Bike to retailers | 1.7 | 1.7 |
| Subtotal | 1.79 | 1.79 |
| Total cost | 380.79 | 434.55 |

Table 4. The LCC in consumer perspective (Euro) [9, 38]

| Item | Bamboo-frame bicycle | Aluminum-frame bicycle |
|---|---|---|
| Bicycle purchase price | 945 | 609.5 |
| Tyres | 180 | 180 |
| Turn-back discount | 94.5 | 60.95 |
| Total cost | 1030.5 | 728.55 |

### *2.4. SLCA*

The goal of the SLCA is to assess the social conditions for the workers and the local communities in China and Guinea involved in the raw material extraction and raw material processing, and the workers, the consumers and local communities in Germany [9]. China and Guinea are developing countries which play important roles in international manufacturing and production for exporting resource or raw materials. Via probing the social risks of China and Guinea, we can gain more completed pictures for developing countries. In this study, we adopt data gained by the social hotspot database [46, 47] for China, Guinea, and Germany to digest main social issues. The social hotspots database shows very high importance in China for the following five topics, as well as indicated in Figure 3. [9, 46, 47]:

- Potential of average wage being < non-poverty guideline
- Potential of country not adopting labor conventions
- Risk of not having collective bargaining rights
- Risk of not having the right to strike
- Risk of not having access to improved sanitation (urban).

For Guinea, the 8 types of social risks with very high importance (as shown in Figure 4.) are [46, 47]:

- Overall fragility of legal system
- Overall fragility of gender equity
- Potential of country not passing labor laws
- Risk of population of working > 48 hours per week
- Risk of child labor
- Number of children out of school (male, female, and total)
- Percentage of population living < $2 per day
- Risk of not having access to improved sanitation (rural, urban, and total)

On the German side, as displayed in Figure 5., there is no very high risk of the social hotspots. The only high importance topic is risk of not having the right to strike [9, 46, 47].

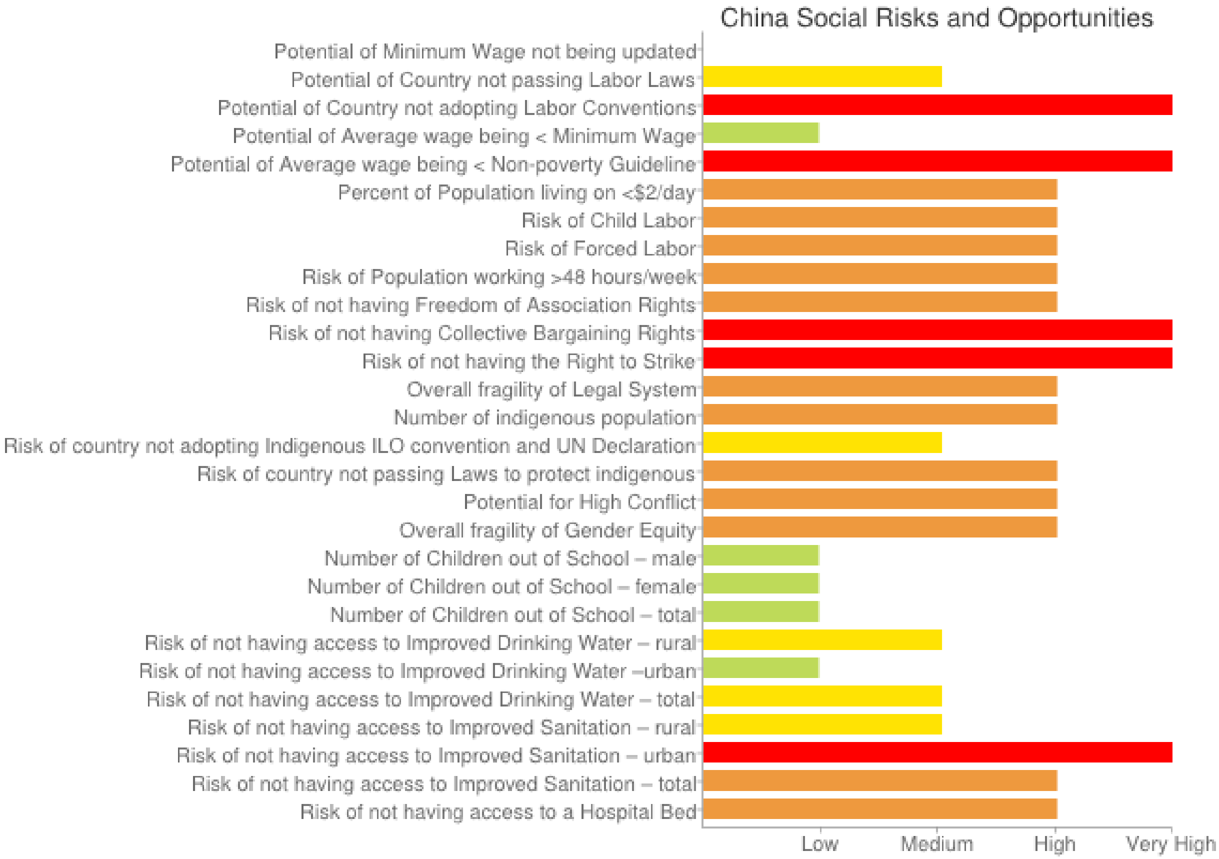


Figure 3. Social risks of China [47]

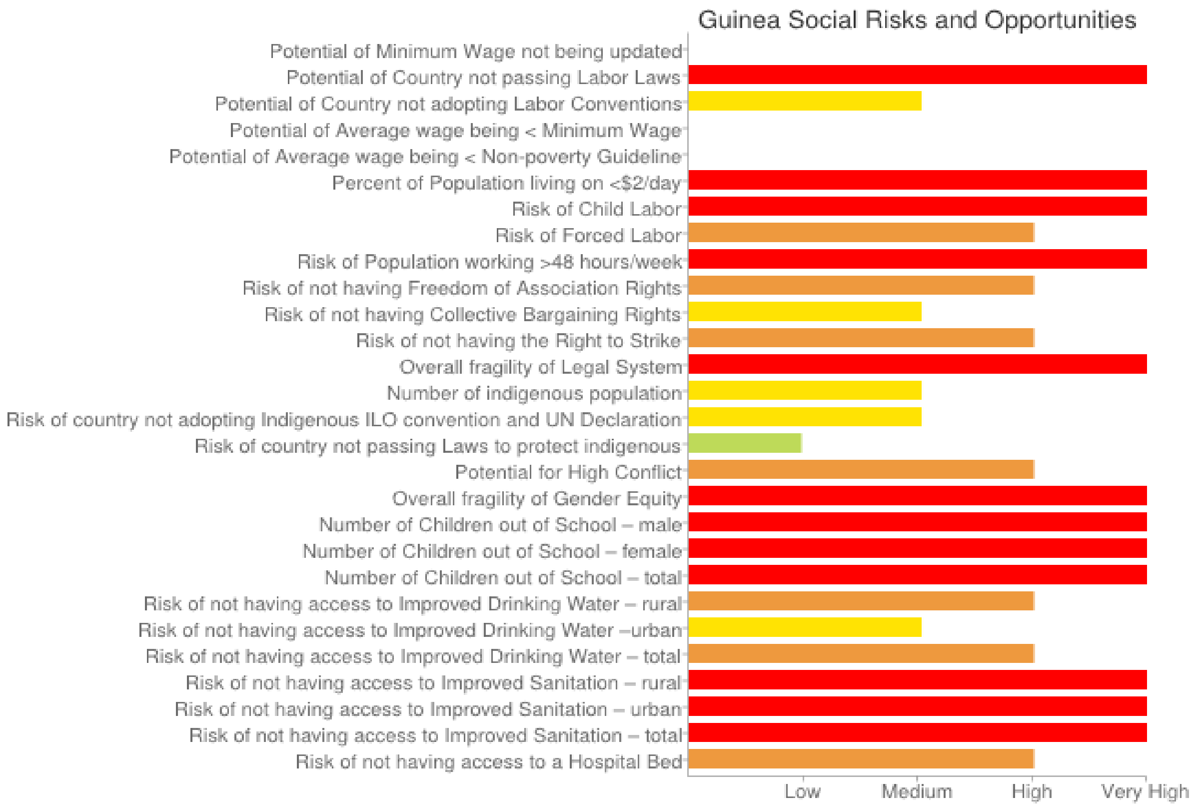


Figure 4. Social risks of Guinea [47]


Figure 5. Social risks of Germany [47]

## 3. Results and Discussion

### *3.1 LCA*

In this study, 18 mid-point ReCiPe Indicators are adopted as the life cycle impact assessment indicators to evaluate the environmental impacts contributed by the two bicycles [9]. As shown in Figure 6. and Figure 7., production of “other parts of bicycles” leads main environmental impacts through the life cycle of the both bicycles. Among “other parts of bicycles,” we find out that electronic components production makes the largest contribution. Besides, in EoL, incinerations of bamboo and plastics produce valuable electricity and steam, providing credits especially in fossil depletion and ionising radiation categories; on the other hand, the incineration leads main environmental impact on freshwater ecotoxicity. Comparing the results expressed in Figure 6. and Figure 7., we can also detect that impacts lead from raw material processing of frame in aluminium-frame bicycle are higher than in bamboo-frame one.

In Figure 8., the results reveal that an aluminium-frame bicycle contribute more environmental impacts than a bamboo-frame bicycle except in ionising radiation and terrestrial acidification. The significant gap in water depletion between the two bicycles may be resulted from the assumption in this case study that only rainfall mainly needed in bamboo plantation (due to no concrete information of irrigation water usage for bamboo plantation).

To highlight the impacts caused by different frames, we choose raw material extraction, raw material processing, and frame production to exercise LCA. As shown in Figure 9., the results indicate aluminium-frame brings out remarkable larger environmental impacts than the bamboo-frame in freshwater ecotoxicity, freshwater eutrophication, human toxicity, marine ecotoxicity, and water depletion. In freshwater ecotoxicity, freshwater eutrophication, human toxicity, and marine ecotoxicity, redmud from bauxite digestion to residual material landfill in aluminium hydroxide production in raw material processing stage contributes the very high portion. In water depletion, electricity used in primary liquid aluminium production in raw material processing is dominant. For bamboo-frame, the sodium tetra-hydroborate usage for bamboo preservation in raw material processing makes the largest contribution in above mentioned impact categories.

In addition, to focus on climate change, the common environmental topic highlighted on the international agenda, we calculate carbon footprint to show the potential caused by the two bicycles. As shown in Figure 10., the aluminium-frame bicycle (237.9 kg $CO_2$-Equiv.) leads higher carbon footprint than the bamboo-frame one (232.5 kg $CO_2$-Equiv.) but not significant. The main difference is the aluminium-frame bicycle contributes more impact in raw material processing phase.

In this case study, the pesticide and irrigation information of bamboo cultivation in China is limited. It may lead under-estimation of environmental burdens caused by bamboo-frame. Due to relying on the database in software, the energy consumption in bauxite extraction in Guinea can be too under-estimated. That means we should probe further in mining activities to reflect real situation. Also, the transportation information in Guinea is not concrete, indicating possible bias in the life-cycle transport evaluation.

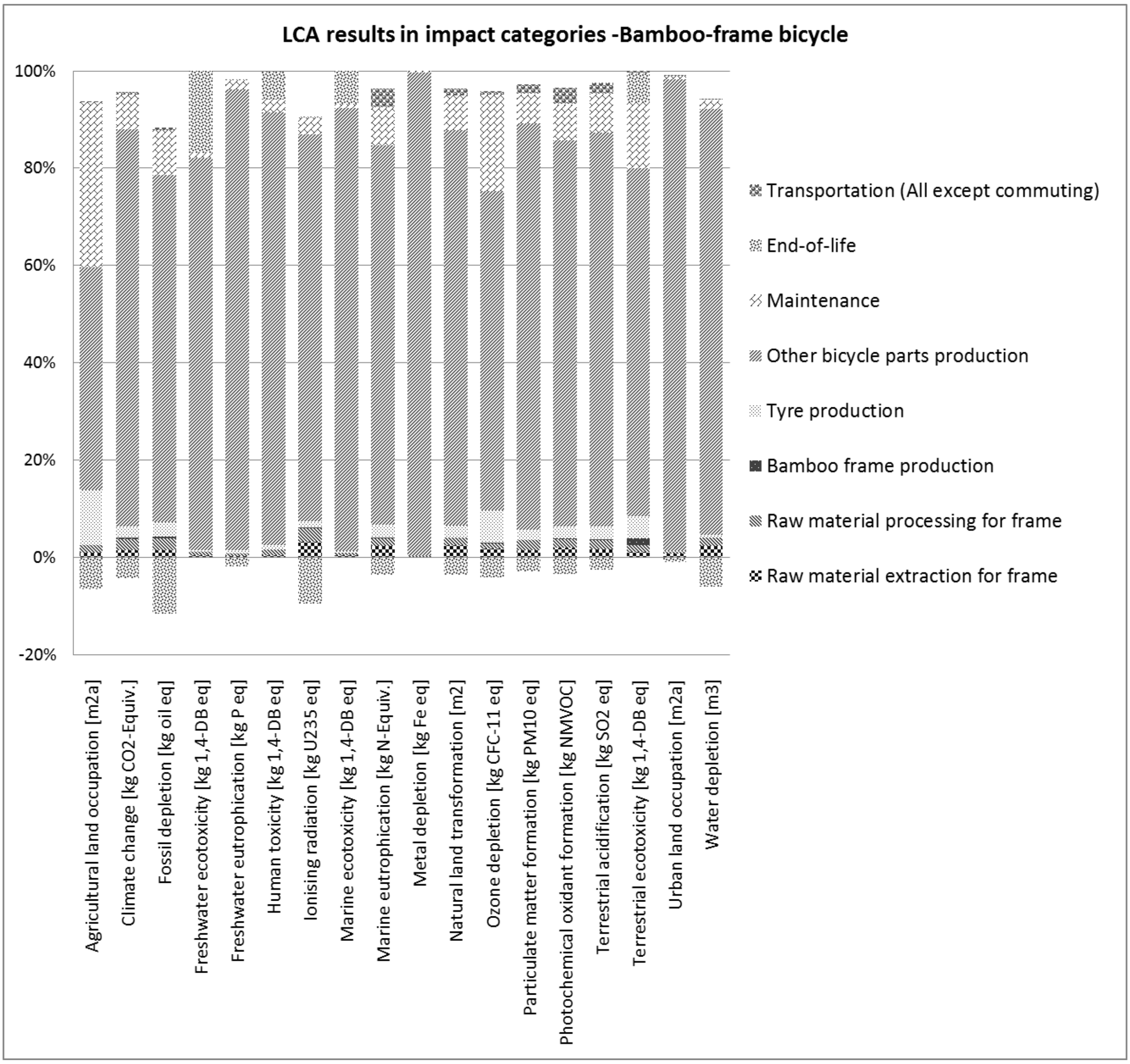


Figure 6. Life cycle assessment results of a bamboo-frame bicycle in ReCiPe impact categories [9]

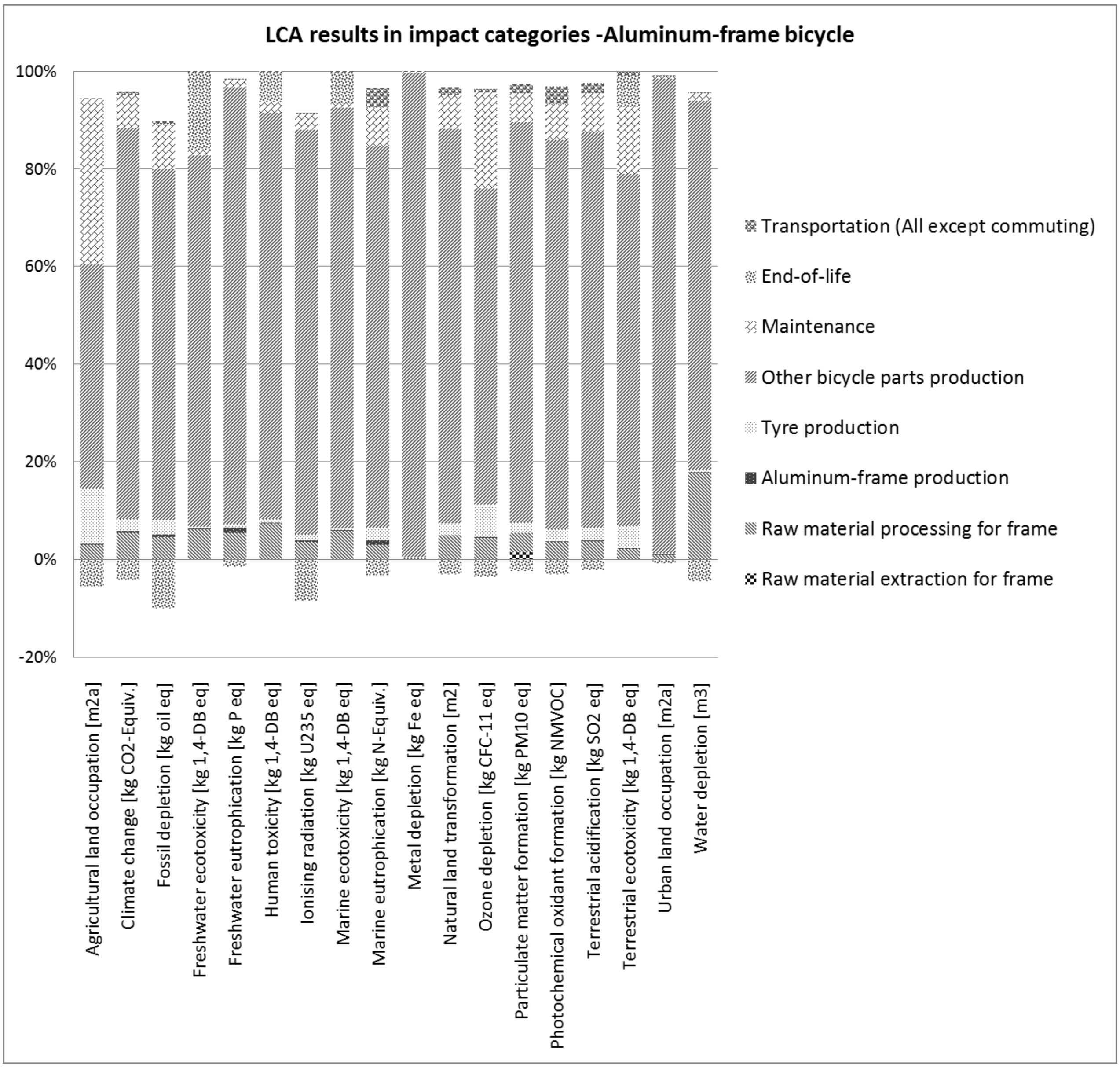


Figure 7. Life cycle assessment results of an aluminum-frame bicycle in ReCiPe impact categories

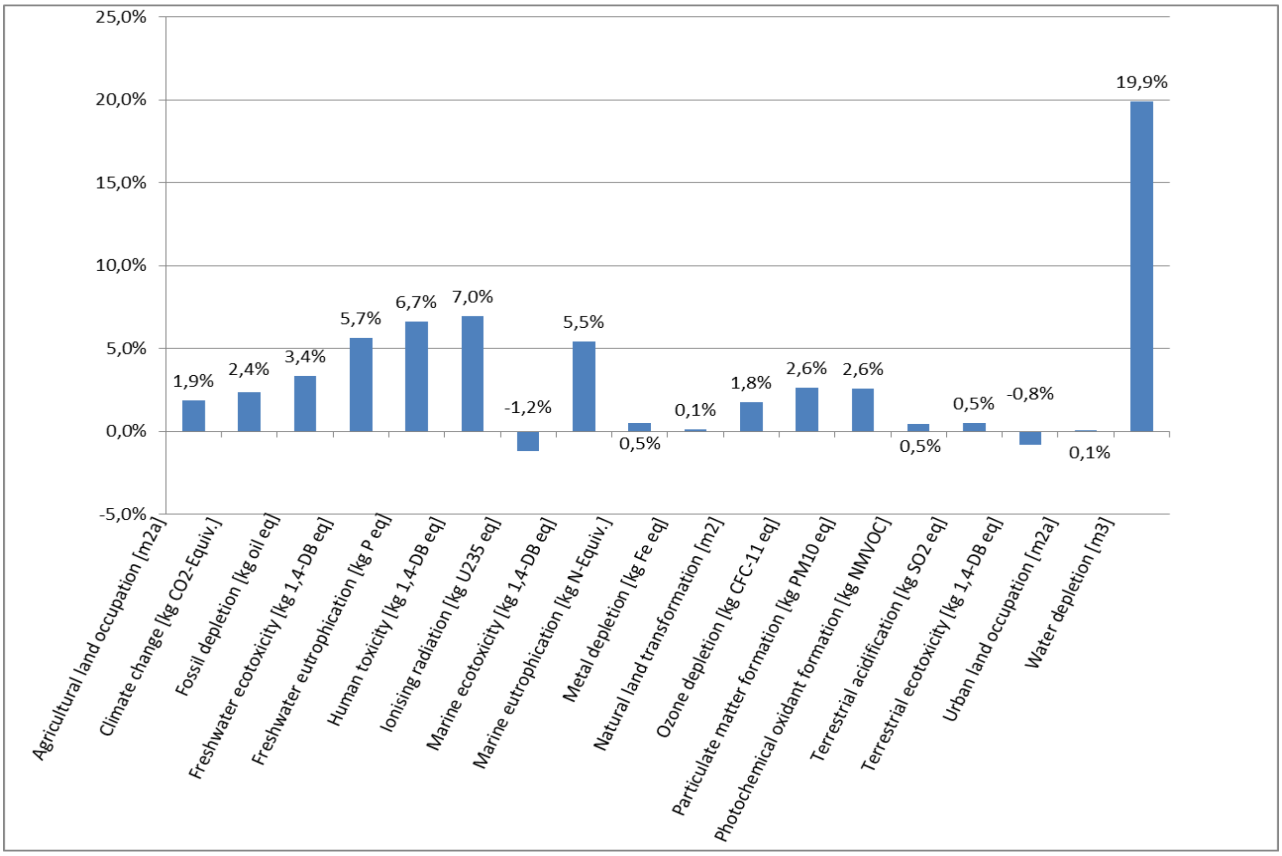


Figure 8. The LCA results comparison of the two bicycles, based on the bamboo-frame bike (%)

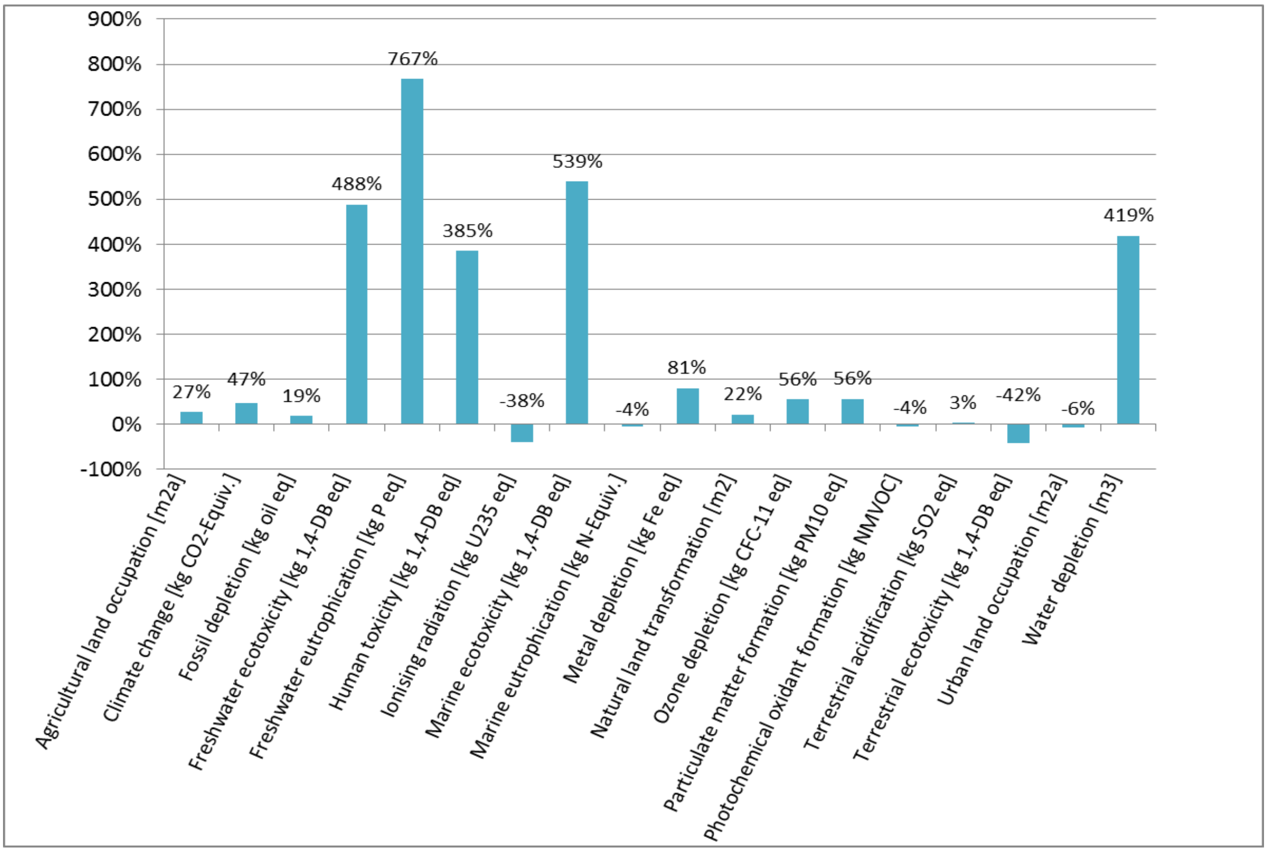


Figure 9. The cradle-to-gate results comparison of the two frame-related production, based on bamboo-frame (%)

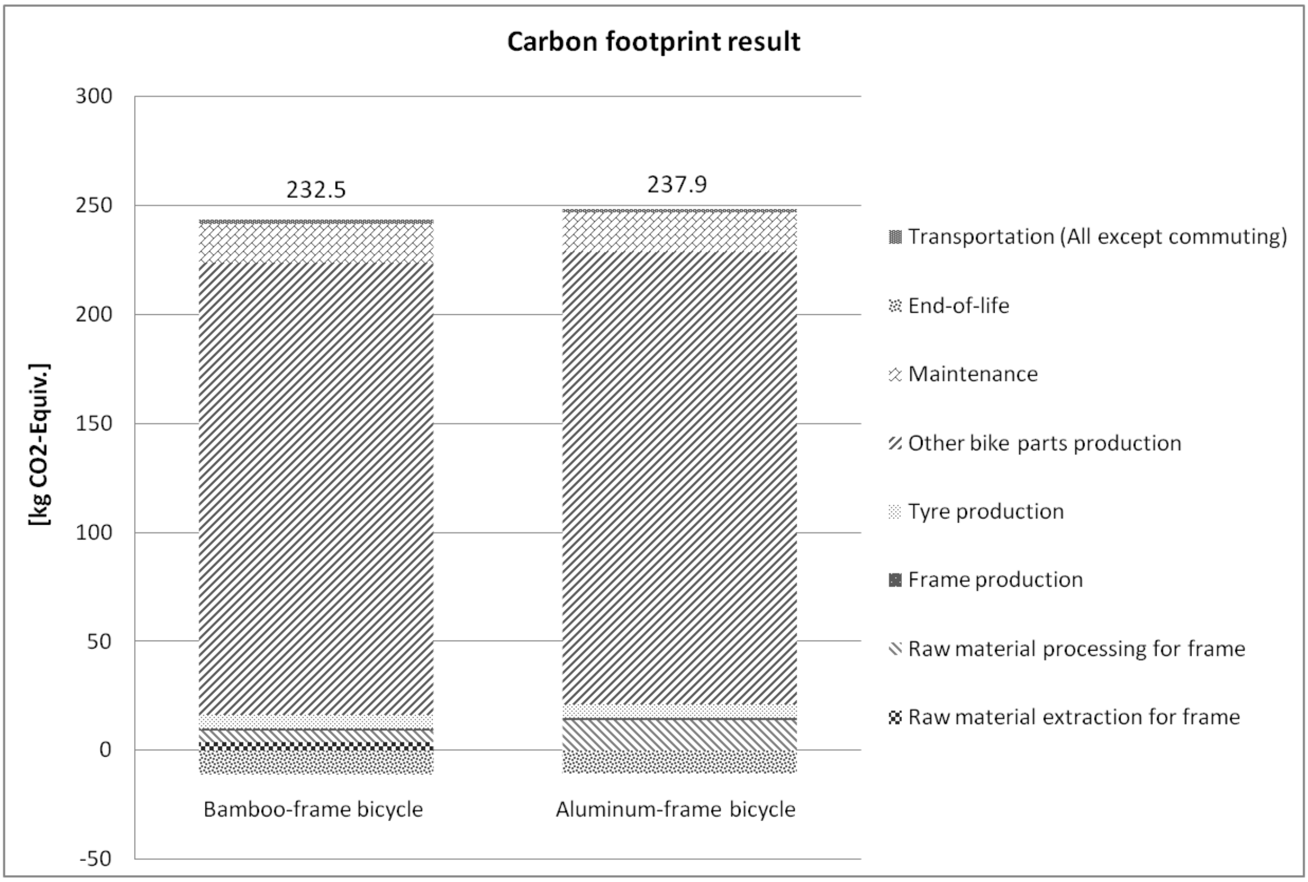


Figure 10. Carbon footprint calculation of the two bicycles [9]

*3.2 LCC*

In the manufacturer perspectives, LCC of a bamboo-frame bicycle is lower than an aluminum-frame ones', but in contrast, LCC of a bamboo-frame bicycle is higher than an aluminum-frame ones' in consumer perspective. The overall results represent that calculation in different perspective can lead the LCCs in various ways. In manufacturer perspective, the cost of a bamboo-frame bicycle (434.55 €) is a little more than aluminum-frame ones' (380.79 €) due to the main cost difference between the two frames. The acquisition costs play a dominant role, accounting for about 93% in total cost for manufacturers; in addition, labor costs seize 5.4 -6.1%, and transportation costs occupy 0.4-0.5% of the total cost, as shown in Figure 11.

In consumer perspective, the cost of a bamboo-frame bicycle (1030.5 €) is significant more than aluminum-frame ones' (728.55 €). As same as the situation in manufacture perspective, the acquisition costs is major part of total costs: 77.5% in a bamboo-frame bicycle, 71.67% in an aluminum-frame one. Maintenance costs take the second dominant place of the total cost, in 14.76-21.17 %; the salvage value can contribute the cost deduction in near 7-8% of total costs. The portions of cost categories are expressed in Figure 12.

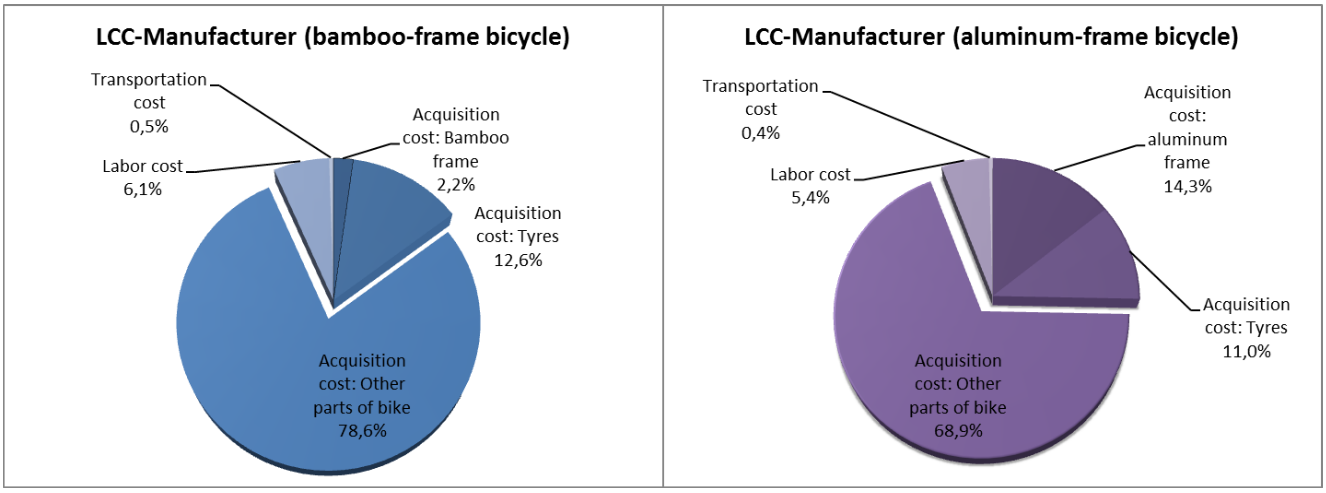


Figure 11. The portions of LCC categories in manufacturer perspective for the two bicycles

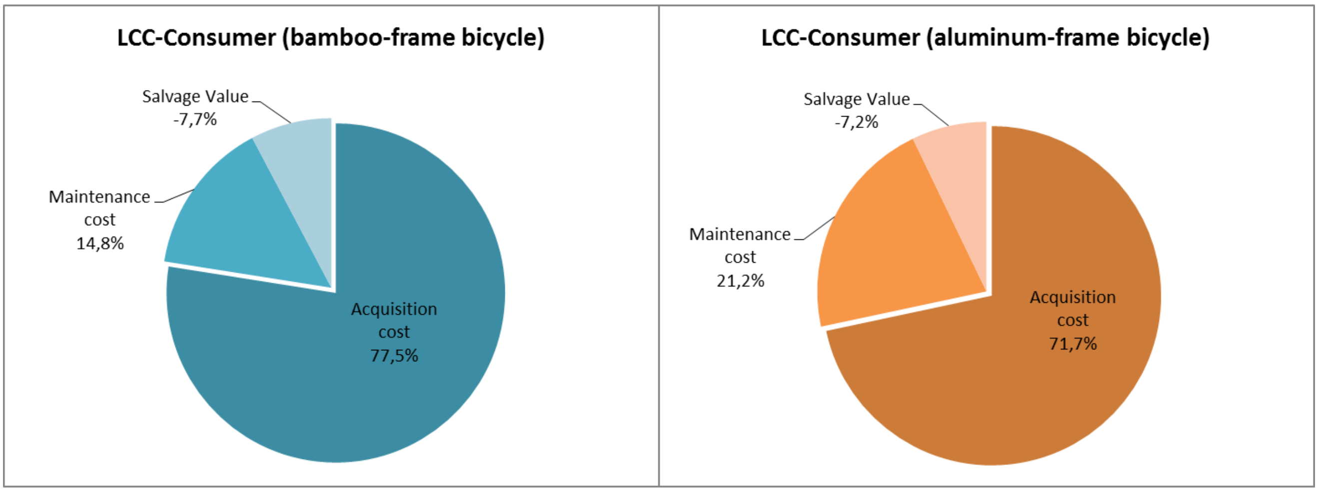


Figure 12. The portions of LCC categories in consumer perspective for the two bicycles

In this study, the LCC results may be limited since the topics: (1) transportation cost in China and Guinea are simply assumed that included in frame purchase price; (2) the time issue of currency is ignored; and (3) consumer behavior of transporting bicycles and disposing the used bicycles can be really various and unpredictable (4) the purchase price of aluminum-frame bicycles varies in large gap, how to measure the price is still in challenge.

*3.3 SLCA*

China's economy is the second largest economy with near 1.34 billion of population [9, 48]. However, in the rapidly growing economy, the average wage in China is only $1.04 per hour in 2011 [49, 50]. According to the non-poverty wage methodology [51], the non-poverty level for China was 1.49 US$ per hour [50-54]. The non-poverty level is higher than the average wage for 43% [55], showing the severe poverty situation. Focus on the main bamboo origin, Anji region of Province Zhejiang, the average wage of the overall province is $3.47 per hour, but the minimum wage for Anji region is only $0.95 [50, 56, 57]. The average wage of the overall province is almost 3.67 times of the minimum wage of Anji region, indicating that even in the same province the salary may be distributed unequally. Moreover, the minimum wage of Anji region is already under the non-poverty level.

In labor issues, China has not ratified the International Labor Organization (ILO) Convention on freedom of association, and the right to Organized and Collective Bargaining [9, 58]. Under the situation which only the All China Federation of Trade Union (ACFTU) is recognised in law and operates monopoly, workers have no real right to express their opinion for negotiation [9]. Strikes are often repressed with police force and are not supported by the official trade union. The only allowed action is in the form 'health and safety work stoppages [9, 58]. In addition, according to the World Bank, about 74% of the urban population in China have access to improved sanitation facilities [9, 48]. Since China dedicates to develop their main cities to large commercial areas, more and more people (the urban population is 0.6 billion in 2011 [48]) have moved in urban sites. It reveals the importance of improved sanitation facilities [9].

The results from social hotspots database indicate that Guinea has main social problems in fragility of law system and gender equity, insufficient wage standard and record, low living and sanitation standard, and high drop-out rate with large amount of child labor [47]. In Guinea, government is corrupt and fail to punish people who against the law including violent abuse [59]. The security force of government harasses opposition members and journalists. Moreover, arbitrary arrest, prolonged pretrial detention, incommunicado detention, life-threatening prison condition, and lack of judicial independence are critical issues contributing unstable law system and society [59].

Next, rape is a common criminal offense in Guinea but rarely prosecuted; meanwhile, sexual harassment is not against the law. About 20% of women treated in hospitals are victims of sexual assaults [59]. There are harmful traditional practices, Female Genital Mutilation (FGM). FGM is illegal but widely practiced (96% of women) in all regions, causing high rates of infant and maternal mortality [59]. The government cooperated with NGOs to try to eradicate FGM and educate health workers for the dangers of the practices [59]. Besides, polygyny is common marriage situation [59]. The divorce law tends to favour men in awarding custody and assets; also, in practice women receive lower pay then men for equal works [59].

Since the bauxite-alumina sector has been by far the country's leading sector for the decades, probing the social risks can meaningfully represent the labor and working conditions in mining industry [60]. Acceptable working conditions in Guinea are still topics needed to be improved. The Ministry of Labor receives inadequate training and equips limited resource, to construct and to exercise concrete labor laws[59]. Penalties for violation of the labor law are barely sufficient to deter the illegal cases. The government has neither exercised minimum wage provision nor promoted standard although [59]. There are laws mandating regular works should not exceed 10-hour days or 48-hour weeks, but authorities rarely monitor work practices and enforce the rules [59]. Under the same circumstance, the labor law contains general provisions related to safety and health but without establishing practical standards [59]. Moreover, the laws prohibit all forms of child labor, but with deficient penalties, many children between 5 to 16 years old keep working 10 to 15 hours a day in mining industry for minimal compensation and little food [59].

Government policy provides tuition-free compulsory primary education for 6 years but actually many children break school off for working or begging [59]. According to World Bank record, the primary completion rate of relevant age group is about 64% in 2010 [48]. Due to high possibility of sexual harassment and the concern of unwanted pregnancies, girls' attendance becomes lower (the primary completion rate for female is only 53% in 2010, for male is near 75%) [48, 59]. In poverty issue, about 70% of population live under $2 a day. The poverty may lead drop-out rate increased as well as enlarging child labor population. Despite the living standard indicated in currency, the condition of sanitation is also a topic we should concern on. The percentage of population with access to improved sanitation facilities overall is 18%; for rural is 11%, in urban is 32% [48]. The severe sanitation situation can cause illness easily which may relate to the low life expectancy, 53.6 years [48].

The only high concern in the Hot Spot Database for Germany is the risk of not having the right to strike [9, 47]. Even though Germany has signed international conventions on the right to strike on a general basis, this is still limited for the professional group civil servant [61]. However, the professional group working in the bicycle manufacturing in Germany is not civil servant but unskilled or skilled workers. They have the legal right to strike as long this is authorized by the trade union [9].

## 4. Conclusions

This main contribution is applying the integrated sustainability assessment: LCA, LCC and SLCA as a tool for sustainable manufacturing in a practical case study of the bamboo-frame bike and the aluminum-frame bicycle.

The life cycle impact assessment results reveal that the aluminium-frame bicycle contribute more environmental impacts than the bamboo-frame bicycle except in ionising radiation and terrestrial acidification. The other parts of bike production are dominant, especially for the electronic components. Incinerations of bamboo and plastics produce valuable electricity and steam, providing credits in fossil depletion and ionising radiation categories. The aluminium-frame brings out remarkable larger environmental impacts than the bamboo-frame in freshwater ecotoxicity, freshwater eutrophication, human toxicity, marine ecotoxicity, and water depletion. The redmud from bauxite digestion to residual material landfill in aluminium hydroxide production contributes the very high portion; in water depletion, electricity used in primary liquid aluminium production is dominant. For bamboo-frame, the sodium tetra-hydroborate usage for bamboo preservation in raw material processing makes the largest contribution.

The overall LCC results show that calculation based on different perspective can lead the LCCs in various ways. The LCC in manufacturer perspective is estimated to 380.79 € for the bamboo bicycle and 434.55 € for aluminum-frame one. The total acquisition cost (about 93% in both two bicycles) is dominant, especially the cost from purchasing the other parts of bike. Reducing the cost of producing the other parts of bike will be the core topic to reduce the LCC for both the manufacturer; secondly, the purchase price from the user perspective is also needed to decrease.

The common topics in developing countries are low wage, harsh working condition, low living standard, and insufficient sanitation. In China, the right to collective bargaining and the right to strike are restricted both in law and in practice, weakening workers' right in a vicious circle. With high population migrating to urban areas in China, to raise the urban population with access to improved sanitation facilities is inevitable and stringent. As an African developing country, Guinea has severe social problems in fragility of law system and gender equity, insufficient wage standard and record, low living and sanitation standard, and high drop-out rate with large amount of child labor.

Further research would focus on including collect more detailed bamboo cultivation information to reflect reality. Also, the transportation information in Guinea is not concrete, indicating possible bias in the life-cycle transport evaluation. The bamboo-frame and the aluminum-frame bicycle correspondingly stand for the renewable-resource and the conventional type of bicycle. To discuss more in transportation vehicles can be one direction in the future. Meanwhile, the authors will keep further applying sustainability assessment in environmental, economic and social aspects to delicate in improving the structure of the methodology.

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**Conflict of Interest**

The authors declare no conflict of interest.

**References**

1. World Commission on Environment and Development, Our common future. 1987, Oxford: Oxford University Press. xv, 400.
2. Hunkeler, D., Lichtenvort, K. and Rebitzer, G., eds. Environmental Life Cycle Costing. 2008, CRC Press.
3. Swarr, T. E., Hunkeler, D., Klopffer, W., Pesonen, H.-L., Ciroth, A., Brent, A. C. and Pagan, R., Environmental life-cycle costing: a SETAC code of practice. 2011, Pensacola: SETAC Press.
4. Benoît, C. and Mazijn, B., eds. Guidelines for Social Life Cycle Assessment of Products. 2009, United Nations Environment Programme: Paris. 104.
5. Finkbeiner, M., Schau, E. M., Lehmann, A. and Traverso, M., Towards Life Cycle Sustainability Assessment. *Sustainability*, 2010. **2**(10): p. 3309-3322.
6. Klöpffer, W. and Renner, I., Life-Cycle Based Sustainability Assessment of Products, in *Environmental Management Accounting for Cleaner Production*, S. Schaltegger, et al., Editors. 2009, Springer Netherlands: [Dordrecht]. p. 91-102.
7. Klöpffer, W., Life-Cycle based methods for sustainable product development. *The International Journal of Life Cycle Assessment*, 2003. **8**(3): p. 157-159.
8. Finkbeiner, M., Reimann, K. and Ackermann, R., Life Cycle Sustainability Assessment (LCSA) for products and processes, in SETAC Europe 18th Annual Meeting. 2008: 25-29 May 2008, Warsaw, Poland.
9. Schau, E. M., Chang, Y.-J., Scheumann, R. and Finkbeiner, M., Manufactured products – how can their life cycle sustainability be measured? A case study of a bamboo bicycle, in The 10th Global Conference on Sustainable Manufacturing. 2012: Istanbul, Turkey.
10. Iso 14040, Environmental management - Life cycle assessment - Principles and framework (ISO 14040:2006). 2. ed. July 2006 ed. *International Standard*. 2006, Geneva: ISO. 20.
11. Iso 14044, Environmental management - Life cycle assessment - Requirements and guidelines (ISO 14044:2006). *International Standard*. 2006, Geneva: ISO. 46.
12. Guinée, J. B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., De Koning, A., Van Oers, L., Sleeswijk, A. W., Suh, S., Udo De Haes, H. A., De Bruijn, H., Van Duin, R. and Huijbregts, M. a. J., Handbook on life cycle assessment - Operational guide to the ISO standards. *Eco-efficiency in industry and science*, ed. A. Tukker. 2002, Dordrecht: Kluwer Academic Publishers. 692.
13. Klöpffer, W. and Grahl, B., Ökobilanz (LCA): Ein Leitfaden für Ausbildung und Beruf. 2009, Weinheim: Wiley-vch.
14. Lichtenvort, K., Rebitzer, G., Huppes, G., Ciroth, A., Seuring, S., Schmidt, W.-P., Günther, E., Hoppe, H., Swarr, T. and Hunkeler, D., Introduction - History of Life Cycle Costing, Its Categorization, and Its Basic Framework, in *Environmental Life Cycle Costing*, D. Hunkeler, K. Lichtenvort, and G. Rebitzer, Editors. 2008, CRC Press & SETAC. p. 1-6.

15. Leuenberger, M., Frischknecht, R. and Ltd., E.-S., Life Cycle Assessment of Two Wheel Vehicles. 2010.
16. Dave, S., Life Cycle Assessment of Transportation Options for Commuters. 2010, Massachusetts Institute of Technology (MIT).
17. Blondel, B., Mispelon, C. and Ferguson, J., Quantifying CO2 savings of cycling. 2011.
18. Goedkoop, M. J., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J. and Van Zelm, R., ReCiPe 2008 - A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. 2009, VROM Den Haag, The Netherlands.
19. Van Der Lugt, P., Vogtländer, J. and Brezet, H., Bamboo, a Sustainable Solution for Western Europe: Design Cases LCAs and Land-use, in INBAR Technical Report No. 30. 2009.
20. Lou Yiping, L. Y., Kathleen Buckingham, Giles Henley, Zhou Guomo, Bamboo and Climate Change Mitigation. 2010, International Network for Bamboo and Rattan (INBR).
21. Xiao, J. and Yang, X., Transfer of Technology Model: Medium and Large Scale Bamboo Plantations. 2000, International Network for Bamboo and Rattan (INBR).
22. Frandeen, B., Madake Bambusero - The Design and Farbrication of a Bamboo Bicycle. 2012, California Polytechnic State University.
23. Geraldo Ferrer, The economics of tire remanufacturing. *Resources, Conservation and Recycling*, 1997. **19**: p. 221-255.
24. Ralf Bohle Gmbh. Schwalbe-Alle Tour/City Produkte. 2012; Available from: http://www.schwalbe.com/ger/de/produkte/tour_city/.
25. Google Map. Map of approximate distance in Berlin region. 2012 [cited 2012 21.06]; Available from: http://goo.gl/maps/Ws0F.
26. Google Map. Map of approximate distance from Reichshof to Mitte, Berlin, Germany. 2012 [cited 2012 21.06]; Available from: http://goo.gl/maps/xcJu.
27. Searates.Com. Port-to-Port Distances. 2012; Available from: http://www.searates.com/reference/portdistance/.
28. Google Map. Map of approximate distance from Hamburg to Mitte, Berlin, Germany. 2012 [cited 2012 June 21]; Available from: http://goo.gl/maps/SFtB.
29. Bundesanstalt Für Geowissenschaften Und Rohstoffe, Bundesrepublik Deutschland Rohstoffsituation 2009. 2010.
30. Wirtschaftsvereinigung Metalle, Gesamtverband Der Aluminiumindustrie, Gesamtverband Der Deutschen Buntmetallindustrie and Bundesverband Der Deutschen Gießerei-Industrie, Metallstatistik 2010. 2011, WirtschaftsVereinigung Metalle.
31. Classen, M., Althaus, H.-J., Blaser, S., Scharnhorst, W., Tuchschmid, M., Jungbluth, N. and Emmenegger, M. F., Life Cycle Inventories of Metals Data v2.0, in Ecoinvent v2.0 Report No.10. 2007.
32. Google Map. Map of approximate distance from Gelsenkirchen to Mitte, Berlin, Germany. 2012 [cited 2012 October 4]; Available from: http://goo.gl/maps/2Wp81.
33. Hunkeler, D., Lichtenvort, K. and Rebitzer, G., Environmental Lif Cycle Costing. 2008: CRC Press.
34. Finkbeiner, M., Schau, E. M., Lehmann, A. and Traverso, M., Towards Life Cycle Sustainability Assessment. *Sustainability*, 2010. **2**: p. 3309-3322.
35. Alibaba.Com. Price of natural bamboo poles. 2021 [cited 2012 10.10]; Available from: http://www.alibaba.com/product-gs/284645833/Natural_bamboo_poles.html.
36. Ebay. Price of epoxy resin, high performance version of CLR 24 oz 2012 [cited 2012 22.06]; Available from: http://www.ebay.com/itm/EPOXY-RESIN-HIGH-PERFORMANCE-VERSION-MAX-CLR-24-OZ-/310187764669.
37. Cell Bikes. Sell price of Schwalbe Lugano 700x23 Wirebead Tyre 2012 [cited 2012 06.22.]; Available from: http://www.cellbikes.com.au/Schwalbe-Lugano-700x23-Road-Tyre.
38. Steingrímsson, J. G., Personal communication about bicycle manufacturing, E.M. Schau, Editor. 2012, TU-Berlin: Berlin.

39. Bureau of Labor Statistics U.S. Department of Labor, International Comparions of Hourly Compensation Costs in Manufacturing, 2010. 2011, Bureau of Labor Statistics U.S. Department of Labor.
40. Meyer-Rühle, O., Beige, S., Greinus, A., Erhardt, T., Bozuwa, J., Harmsen, J., Kok, R., Kille, C., Hua-Kellermann, N., Roth, M., Burg, R., Röhling, W., (Pm), O. M.-R., Beige, S., Greinus, A., Erhardt, T., Bozuwa, J., Harmsen, J., Kok, R., Kille, C., Hua-Kellermann, N., Roth, M., Burg, R. and Röhling, W., Statistical Coverage and Economic Analysis of the Logistics Sector in the EU. 2008.
41. Stage Truck Co., Truck and Trailer Internal and External Dimensions. 2011.
42. Carl Evers Ohg. Fahrradkarton. 2012; Available from: http://www.kartonfritze.de/Kartonagen/Verpackungskatalog.aspx?cat=\Sonstiges\Fahrradkarton.
43. Jon Gardar Steingrímsson, The average price of an aluminum frame for bicycle manufacturing, Erwin M. Schau, Editor. 2012: Berlin.
44. Fahrrad.De. Purchase price for Serious Cedar Herren black matte. 2012 [cited 2012 10.05]; Available from: http://www.fahrrad.de/fahrraeder/crossraeder/serious-cedar-herren-black-matte/294445.html.
45. Fahrrad.De. Purchase price for BMC Citystreamer CS01 Alivio/Deore men red. 2012 [cited 2012 10.05]; Available from: http://www.fahrrad.de/fahrraeder/trekkingraeder/bmc-citystreamer-cs01-aliviodeore-men-rot/286893.html.
46. Norris, C. B., Aulisio, D. and Norris, G. A., Working with the Social Hotspots Database - Methodology and Findings from 7 Social Scoping Assessments, in 19th CIRP International Conference on Life Cycle Engineering. 2012: Berkeley, USA.
47. Benoît, C. and Norris, G. Social Hotspots Database. 2012 [cited 2012 09.27.]; Available from: http://www.socialhotspot.org/.
48. The World Bank. World Databank. 2012 [cited 2012 September 27 ]; Available from: http://databank.worldbank.org/data/home.aspx.
49. Averagesalarysurvey.Com. Average Salary In China. 2012; Available from: http://www.averagesalarysurvey.com/article/average-salary-in-china/15201531.aspx.
50. European Central Bank. Exchange Rates. 2012; Available from: http://sdw.ecb.europa.eu/home.do.
51. Sweatfree Communities. Non-Poverty Wages for Countries Around the World. 2009 [cited 2012 June 27]; Available from: http://www.sweatfree.org/nonpovertywages.
52. United States Cencus Bureau. Poverty Thresholds by Size of Family and Number of Children. 2012; Available from: http://www.census.gov/hhes/www/poverty/data/threshld/index.html.
53. Central Intelligent Agency (Us). The World Factbook. 2012 [cited 2012; Available from: https://www.cia.gov/library/publications/the-world-factbook/index.html.
54. Ministry of Human Resource and Social Security of the People's Republic of China. Human Resources and Social Security Development Statistics 2011 2012; Available from: http://www.mohrss.gov.cn/page.do?pa=8a81f3f1314779a101314a86e7450406.
55. Benoit, C., Norris, G., Aulisio, D., Rogers, S., Reed, J. and Overaker, S., Social Hotspots Database - Risk and opportunity table development 2010. 2010.
56. Zhejiang Province Human Resource and Social Security Bureau. The minimum wage of Zhejiang Province, China in 2012. 2011 [cited 2012; Available from: http://www.zjhrss.gov.cn/art/2011/4/8/art_1161_2121.html.
57. Zhejiang Province Human Resource and Social Security Bureau. The average wage of Zhejiang Province, China in 2011. 2012 [cited 2012; Available from: http://www.zjhrss.gov.cn/art/2012/6/7/art_1161_3921.html.
58. International Trade Union Confederation (Ituc), Internationally recognised core labour standards in the People's Republic of China. 2010, International Trade Union Confederation: Geneva. p. 1-7.

59. Bureau of Democracy Human Rights and Labor, Country Reports on Human Rights Practices for 2011-Guinea. 2011, Bureau of Democracy, Human Rights and Labor, United States Department of State
60. Bonnie Campbell, Environmental Policies, Mining and Structural Adjustment in Guinea. 1997, Département de Science Politique, Université du Québec à Montréal.
61. Bureau of Democracy Human Rights and Labor, Country Reports on Human Rights Practices for 2011-Germany. 2011.