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SUSTAINABILITY ASSESSMENT OF INDUSTRIALIZED BAMBOO SOLUTIONS FOR HOUSING PROGRAMS IN THE PHILIPPINES

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Abstract

Rapid population growth and urbanization have created an unprecedented need for housing solutions worldwide. In the Philippines, it is estimated that more than one hundred thousand additional housing units are needed every year. The housing demand in the Philippines is further increased by the severity and number of natural disasters that affect the country every year. Many organizations work in the country to support the development of reconstruction and social housing projects. The most common construction systems implemented in such projects use concrete in the form of blocks and/or other structural elements. These systems are energy intensive and have high levels of greenhouse gas emissions. It has been proposed that those emissions can be reduced through the use of bamboo-based construction systems because bamboo is able to sequester high levels of CO_2 during its growth and potentially store it during the building's lifespan. The present research aims to assess the sustainability of industrialized bamboo-based construction solutions, such as glue laminated bamboo, in housing projects. Life Cycle Assessment was used to characterize the environmental aspects, CO_2 crediting was used to examine the economic aspects and job creation potential measured the social aspects. The results show that the most important variables are the lifespan of the bamboo-based buildings and their end-of-life scenarios. Moreover, because there are currently no managed bamboo or wood forests in the Philippines, the results show that the transition toward a more sustainable built environment will be much faster with the implementation of small- and medium-sized bamboo production facilities compared with industrial wood production. However, the potentially shorter service life of bamboo-based buildings will require higher maintenance and a careful management of the end of life of the product to efficiently store the CO_2.

Keywords:

Bamboo, Sustainability, Life Cycle Assessment, Housing Projects

1 INTRODUCTION

Rapid population growth and urbanization have created an unprecedented need for housing solutions worldwide [UNHabitat 2011]. In the Philippines, it is estimated that more than one hundred thousand additional housing units are needed every year [UNESCAP 2011]. The housing demand in the Philippines is further increased by the severity and number of natural disasters that affect the country every year [Guha-Sapir, Vos et al. 2012]. Many organizations work in the country to support the development of reconstruction and social housing projects. The most common construction systems implemented in such projects use concrete in the form of blocks and/or other structural elements [Wallbaum, Ostermeyer et al. 2012]. These systems are energy intensive and have high levels of greenhouse gas emissions. It has been proposed that those emissions can be reduced through the use of bamboo-based construction systems because bamboo is able to sequester high levels of CO_2 during its growth and potentially store it during the building's life span [Murphy, Trujillo et al. 2004, Archila-Santos, Ansell et al. 2012, Vogtländer, van der Velden et al. 2013]. Moreover, the use of bamboo-based construction materials can bring associated benefits, such as job creation and improved livelihoods in both rural and urban areas [Sánchez-Morales and Leiva-Mora 2011]. These factors open the doors for new approaches to sustainability in which human activity does not deplete natural resources and in which a partnership is established to generate benefits for both humans and the environment [Reed 2007]. This approach has been called regenerative development, and in terms of sustainable construction, it means that the best buildings should provide net positive benefits and improve the surrounding society and environment [Pedersen 2009, Mang and Reed 2012].

Two construction systems have been identified for the production of bamboo-based buildings. One uses round bamboo poles to create load-bearing walls [Zea Escamilla, Habert et al. 2014], and the other uses glue-laminated bamboo elements similar to laminated wood elements [De Flander and Rovers 2009, Xiao 2009]. The traditional system using round bamboo is meant only for low-rise buildings, with a maximum of two stories [AIS 2004], and uses a significant amount of concrete as reinforcement and plaster [Murphy, Trujillo et al. 2004, Zea Escamilla, Habert et al. 2014]. This system is thus not suitable for cases where multi-story buildings are needed because such building require a very specific structural design. It had been proposed that the use of glue laminated bamboo can bridge some of those gaps, thereby allowing for more industrialized production of construction materials, ease of design [Zea Escamilla 2008, De Flander and Rovers 2009] and increasing the number of stories to make buildings more suitable in a dense urban context. Glue laminated bamboo is a composite of bamboo slats and a lamination resin or binder, as shown in figure 1. This material is ready available, but its application to this point has been relegated to furniture and flooring [van der Lugt, Vogtländer et al. 2009]. However, the mechanical characteristic of glue laminated bamboo are similar to those of glue-laminated wood [Zea Escamilla 2008], which makes it suitable for housing construction [Wang, Shyam et al. 2009, Xiao 2009].

Figure 1 Glue laminated bamboo

The present research aims to assess the sustainability of industrialized bamboo solutions, such as glue-laminated bamboo, in housing projects by assessing its environmental impacts in terms of CO_2 emissions, the job creation potential associated with the production of bamboo-based construction materials, and the potential CO_2 credits generated.

2 METHODOLOGY

Three categories were defined to assess the sustainability of industrialized bamboo solutions: environmental accounting for the CO_2 emissions from the production of industrialized bamboo-based housing units; economic accounting for the potential income from CO_2 crediting from carbon storage and avoided emissions, and social accounting for the potential job creation from production of industrialized bamboo construction materials. The results from these categories were also calculated for glue-laminated wood and concrete. The results for all construction materials were compiled and benchmarked for comparison and analysis.

2.1 Environmental impact category

This category assesses the environmental impacts associated with the production, use and disposal of industrialized bamboo solutions for housing programs, in terms of the CO_2 emitted.

Mass Flow Model

The first step in the sustainability assessment was to develop mass flow models for industrialized bamboo and laminated wood. These models consider material flows through the production, use, and disposal of the proposed construction materials. The output flows of one process are the sum of its input flows, accounting for all masses. These models are very useful for visualizing the different streams of matter and to identify the hotspots where emissions are produced. Furthermore, they illustrate the relation between the land required to produce bamboo and wood and the resulting number of housing units that can be produced. For this model, the comparison unit was a housing unit with a total floor area of 175 m^2. The volume of material needed to provide both the frame structure and cladding was 21.9 m^3. The following inputs were used on the mass flow model:

One hectare of managed bamboo plantation can yield 395.1 tons of bamboo poles at 80% moisture content, on a four-year rotation. The first harvest has a six-year delay to account for the establishment of the plantation [Riaño, Londoño et al. 2002]. Overall, 10.3 tons of biological waste (dry weight) were produced during the extraction process per hectare each time. Further, 296.6 tons of water are released during the technical drying process, after which the bamboo pole has a moisture content of 20%. In the processing of bamboo poles into slats for glue-laminated bamboo, 60% of the raw material is lost [Van der Lugt, Vogtländer et al. 2008]. Therefore, 39.55 tons of slats are obtained from this process. In the production of glue-laminated bamboo, a resin content of 1.8 tons was used. The total mass of glue-laminated bamboo obtained from a harvesting cycle of 4 years is 41.41 tons per hectare.

Dynamic CO_2 Model

To model the CO_2 flows in the production of construction materials, it is necessary to consider the time at which CO_2 emissions occur and when it is sequestered and/or stored. This requires a level of complexity that the mass flow model cannot directly handle. To bridge this gap, a dynamic model was developed. In the dynamic CO_2 model, all carbon dioxide inflows and outflows related to the life cycle of the bamboo- or wood-based construction materials were considered. These include the sequestration phase during plant growth, emissions related to the processing and production of construction materials and buildings, the storage phase accounting for the life span of buildings, and the disposal phase that considers the end of life scenarios for the construction materials from the demolished buildings. In these phases, two scenarios were considered: 1) business as usual, where there is no energetic gain from the disposed materials, and 2) using the disposed materials to generate electricity, thereby avoiding emissions of CO_2 from electricity production from non-renewable resources. The dynamic model considers the output of one hectare of plantation that is run for 90 years by the housing program. This means 22 harvest cycles when bamboo is grown and six harvest cycles when wood is planted.

To calculate the CO_2 emissions of these phases a life cycle assessment was carried out. The functional unit for this assessment was 1 kg of bamboo- or wood-based construction material. The life cycle inventories for the glue-laminated bamboo were based on the work of Van der Lugt et al [2009] and Zea Escamilla et al [Zea Escamilla and Habert 2014]. The data for other process and products were based on the EocInvent v2.7 [SCLCI 2011]. The impact assessment was carried out using the IPCC 100a evaluation method [McCarthy 2001] and the SIMApro v7.3 software [Pre-Consultants 2012]. Sensitivity analyses were carried out considering factors such as the building life span, end-of-life use of disposed construction materials, and the electricity mix used.

In the CO_2 dynamic model, the emitted, stored, and avoided CO_2 are accumulated over time. The emitted CO_2 has a negative value, whereas the stored and avoided CO_2 are considered positive. The CO_2 balance per activity was calculated by adding the CO_2 emissions to the CO_2 stored and/or avoided, depending on the activity. These values were then cumulated over the total length of the activity in years.

Housing program dynamic model

The dynamic CO_2 model was further developed to account for the number of houses planned for the housing program. The model considers that the first phase of the program will establish the required bamboo plantations and that only after 6 years can the first housing units be developed. The maximum number of housing units per year is 37000 units, which requires 55000 ha of managed bamboo plantations to be established. The model considers that CO_2 is being sequestered in the growth phases of the bamboo or wood. Then, this CO_2 is stored on the bio-based construction materials used for the housing units. Furthermore, the model assumes that the CO_2 will be released at the disposal phase, which can be done with or without energetic gain. In the second case, the CO_2 emissions are considered avoided emissions. This model is the basis for the assessment of the economic and social categories.

A CO_2 balance is again established at the housing program level, balancing the total CO_2 emissions associated with the production of all housing units with the captured and stored CO_2 in buildings. As a base scenario, it was established that the housing unit will have a life span of 40 years. After this period, the housing units will be demolished, and their construction materials (bio-based) will be used as fuel for electricity production. In this phase, the model will add to the balance the amount of CO_2 avoided from this activity.

2.2 Economic category

This category assesses the potential CO_2 credits that can be generated from using industrialized bamboo for housing. These credits can be traded to produce an additional source of income for the organizations and companies involved on the program. Two types of CO_2 credits can be obtained: the first is for carbon that is permanently sequestered and stored in materials, products, and/or buildings, and the second is for the avoided emissions from electricity production from construction material by-products and the recycling of demolished housing units. The methods used to calculate the stored CO_2 are still under development and discussion, but the International Panel for Climate Change (IPCC) acknowledges the ton-year approach [Fearnside 2002] as a valid accounting system for such emissions. In this approach, the years for which a certain amount of carbon is maintained are counted and awarded credits. Other strategies have also been developed, such as dynamic life cycle assessment, which accounts for time while assessing the potential impact of life cycle greenhouse gas emissions [Levasseur, Lesage et al. 2012].

The economic category assess four types of CO_2 that can be awarded credits: 1) CO_2 captured by the bamboo plantations during their growth, 2) CO_2 stored during the building lifespan, 3) avoided CO_2 emissions from the co-generation of heat and electricity, and 4) avoided CO_2 emissions by recycling the construction materials after the housing units are demolished. These types of CO_2 can be awarded two types of credits: 0.01CHF.CO_2EqTon for capture and storage or 5CHF.CO_2EqTon [Lang 2013] for avoided CO_2 emissions. The annual credits for captured CO_2 are calculated based on the amount of biomass on the plantation, assuming that it accumulates biomass steadily over the year. These annual returns are then added over the period in which the plantation is in production. To credit CO_2 stored in housing units this should have at least a life span of 40 years and considers the CO_2 that is embodied on a housing unit. The returns of this category are cumulated over the lifespan of the housing unit and become zero once the housing units are demolished. The credits for avoided CO_2 emissions are calculated based on the CO_2 balance for the activities where the by products can be used as fuel for electricity production, in this case, including the production of material and the recycling of demolished construction materials from the housing units.

2.3 Social category

This category is assessed in terms of the potential job positions associated with the production of construction materials. The jobs created during the construction of housing units are considered independent of the construction material used and are thus not included in this category. The work of Sánches [2011] showed a relation between the size of bamboo plantations and the number of jobs created. To assess this potential, the amount of land necessary to provide sufficient construction materials for the housing program was calculated. Furthermore, land availability was estimated to be approximately 55000 ha, which is considered “unproductive or unclaimed land” in the Philippines [Knoema 2013]. This figure represents 0.2% of the total land in the Philippines. This type of land is often not appropriated for agricultural or forestry applications but is usually suitable for the cultivation of bamboo. To compare the additional job creation potential that bamboo presents compared with other construction materials, three job creation levels were delineated: low, below 2,500 jobs associated with the production of materials over the housing program execution; middle, 2,500–6,000 associated jobs; and high, above 6,000 associated jobs.

2.4 Sustainability assessment

For the sustainability assessment of the industrialized bamboo solutions, a benchmark was developed that combines the three proposed assessment categories, environment, economic and social. The results for the environment category are located on the x axis, and the results for the cost category are on the y axis. The results for the social category are represented on a colour scale, with low job potential creation in red; middle job potential creation in yellow; and high job potential creation in green. The results for glue-laminated wood and concrete hollow blocks are also displayed.

3 RESULTS

In this section, the results for the three proposed assessment categories—environment, economic and social—are presented, along with the integration of these results into a sustainability assessment benchmark. The main results represent the calculations for bamboo-based products. For validation, the same calculations were carried out for glue-laminated wood and concrete hollow blocks as construction materials.

3.1 Environmental impact category

Mass flow model

The mass flow for the production of one housing unit is presented in figure 2. From this figure, it is possible to observe that a large amount of the mass coming from the plantation is water contained in the bamboo poles. Furthermore, due to the planning and trimming process to which the poles are subjected to produce laminated bamboo, 60% of the mass is converted into a by-product. These results show that is of great importance to reduce the transport distance between the extraction site and the drying facility. Moreover, the efficiency of the transformation from bamboo pole into glue laminated bamboo needs to be improved.

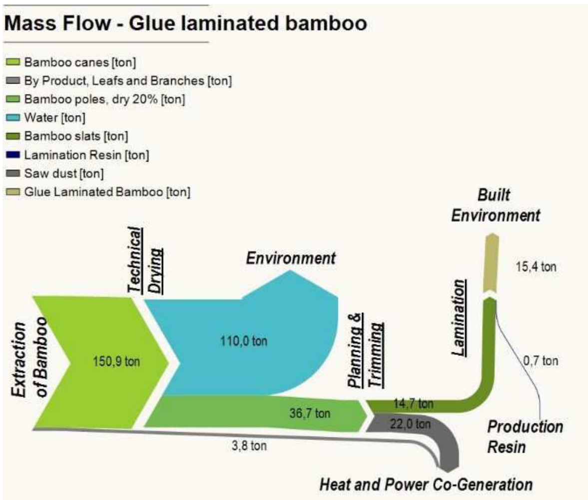

Figure 2 Mass flow for one glue laminated bamboo housing unit

The mass flow model shows that the production of one year of one hectare of bamboo plantation can be processed into enough materials for two housing units.

Dynamic Model Housing demand

The CO_2 flows associated with the execution of industrialized bamboo-based housing solutions are presented in figure 2. This figure presents two types of CO_2 temporary storage (captured in the plantation and stored in buildings) and two types of avoided CO_2 emissions (avoided in electricity generation with material by-products and recycling demolished construction materials). The level of captured CO_2 first increases during the bamboo plantation's establishment period and then has a 25% reduction once the extraction of poles begins. These values stay stable during plantation operations because the amount of bamboo that is extracted is equal that the amount that is regenerated. The CO_2 stored in plantations reaches $4.5x10^6$ CO_2.Eq.Ton after the first 10 years of operation. In the case of stored CO_2, the values grow steadily up to 40 years when the first housing units are demolished and their materials are used as fuel to produce electricity. At this level, the amount of CO_2 stored in buildings stabilizes at $32x10^7$ CO_2.Eq.Ton. This process replaces the use of fossil fuels and therefore emissions are avoided. This value increases while there is production of materials reaching a maximum of $21x10^7$ CO_2.Eq.Ton. The same occurs with the avoided CO_2 emissions from the recycling of construction materials, which peaks ($83x10^7$ CO_2.Eq.Ton) once the last housing unit has been demolished.

At the end of the model, the temporary CO_2 storage disappears because the plantations are no longer managed and no new housing units are produced. This leaves the total cumulative avoided CO_2 emissions of roughly $10x10^7$ CO_2Eq Tons over a period of 130 years.

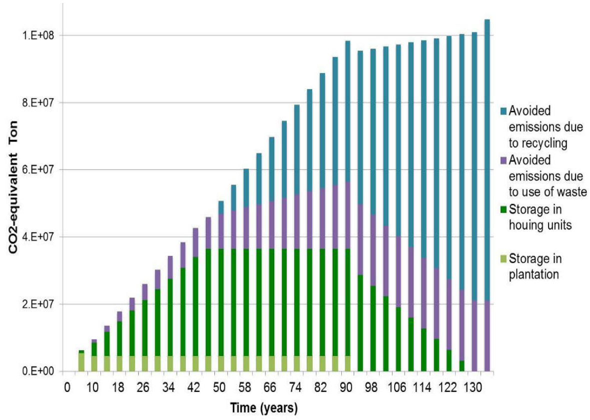

Figure 3 CO_2 dynamic model

From figure 3, it is possible to observe that the model is sensitive to the end of life of the demolished construction materials. If these avoided emissions are not considered, then the final result is significantly reduced. Nevertheless, in both cases, a positive impact on the environment can be achieved by using the industrialized bamboo solutions. Furthermore, these positive impacts have a direct connection with the number of housing units produced and will be limited only by the availability of land to propagate the bamboo.

3.2 Economic Category

The results from this category are related directly to the four types of CO_2 types, as observed in figure 4. It is important to note that the income shown only represents that generated with the potential trade of CO_2 credits while the income generated from the trade of construction materials and housing units is not considered. For the CO_2 crediting calculation, two main categories are considered: temporary storage and avoided emissions. The first is awarded as long as the CO_2 is stored either on plantation or in housing units, but it only receives a small amount per CO_2eqTon on temporary storage and reaches a maximum of $5x10^4$ CHF. The second is awarded every time an emission of fossil fuel CO_2 is avoided and reaches a maximum of $6x10^7$ CHF. The results show that with a project of the proposed dimensions, an average of seven million Swiss francs can be potentially generated from the CO_2 crediting alone. Almost 92% of this income is related to avoided emissions, and only 8% is related to temporary storage. Similar to the environmental category, the results of this category are sensitive to the end of life of the demolished construction materials. If the avoided emissions from this process are not considered, then the total income is reduced drastically, but some income can still be obtained from the temporary storage and the avoided emission during production of construction materials.

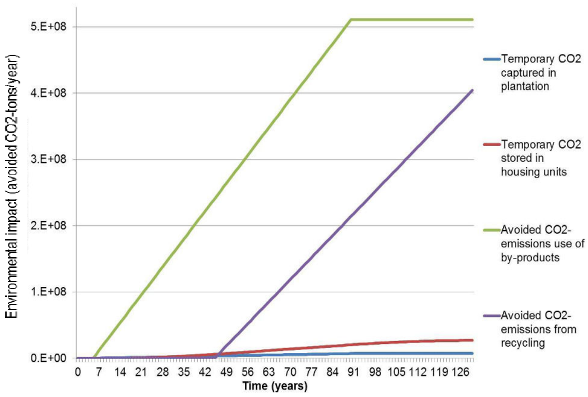

Figure 4 Economic category

3.3 Social category

This category is directly related to the size of the bamboo plantation and the number of factories and workshops that are established to produce glue-laminated bamboo. With a proposed size of 55000 ha, circa 28000 job positions can potentially be created. It can also be considered that such jobs can be created that are specifically targeted to low-income communities in rural and/or semi-urban areas. It must also be noted that bamboo production can be decentralized and established with multiple small-scale operations. The use of unproductive lands also represents a significant improvement of both the environment and livelihood of communities. In this category, glue-laminated bamboo is found to have a high potential, with almost 7,000 job positions potentially created, whereas glue-laminated wood is found to have a middle potential (2,500 jppc) because its production is more centralized and requires long time spans, larger plantation areas, and specific soils for its implementation. Thus, bamboo exists as an alternative that not only improves the environment and livelihoods of communities but also does not compete for land with other activities such as agriculture or forestry. Furthermore, the use of bamboo can allow the regeneration of areas afflicted by deforestation and its associated problems.

3.4 Sustainability assessment

The average results over the study period for the sustainability assessment of glue-laminated bamboo, glue-laminated wood and concrete hollow blocks are presented in figure 5. From this figure, it is possible to observe that under the proposed categories, bamboo provides the most sustainable solution for housing construction. The main advantage of bamboo comes from its rapid establishment (6 years) and growth (4 years), which allows for an early start for producing materials, creating jobs, and stimulating income generation. Moreover, the bamboo plantation is always standing because only 25% of the canes are harvested per cycle [Riaño, Londoño et al. 2002]. This provides a stable income from the temporary storage of CO_2 in the plantation. Using wood products is also a solution, but its applicability is more limited because of its centralized production and the land competition with other human activities. In both cases, however, housing construction reduces both direct CO_2 emissions and indirect emissions from fossil fuels. Both strategies are thus carbon positive. Moreover, jobs and income can be potentially generated from the production and commercialization of housing, the CO_2 credits associated with temporary storage in plantations and housing units, and the avoided emission from the use of by products from the production of materials and demolished construction materials.

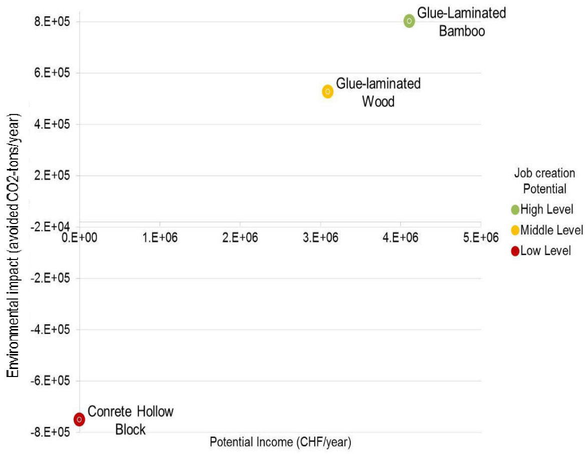

Figure 5 Sustainability assessment

From this figure, it is possible to see that the impacts of glue-laminated bamboo are almost opposite to those of concrete hollow block. Thus, if a program builds 50% of its housing units using glue-laminated bamboo and 50% using concrete hollow blocks, the program could be considered as carbon neutral. However, if the share of industrialized bamboo housing units is increased, the CO_2 balance could become positive.

4 DISCUSSION

This section analyses the sensitivity of the results to the variables, building lifespan, electricity mix, and end of life of the demolished construction. These variables were found to have the largest contribution to the variability of the results and are thus studied in detail in this section.

4.1 Building lifespan

The lifespan of buildings is uncertain and depends not only on the construction materials used but also on the urban, economic, and social dynamics of its place of construction. For this reason, a sensitivity analysis was conducted to assess the effect that short (20 years) and long (60 years) building lifespans will have. Lifespan length is not found to affect the CO_2 stored in plantations, crediting for CO_2 stored in plantations, and the potential for job creation. However, a reduction in the housing lifespan from 40 to 20 years reduces the amount of CO2 stored in the building over time. As a result, the credits for CO_2 stored in buildings are reduced by that amount and are available on an earlier stage. When the housing unit's life span is increased, the CO_2 stored in buildings also rises. Consequently, the credits for temporary CO_2 storage in buildings also increase, but they are available after 60 years when the first housing units are demolished and recycled. This analysis further shows that even under short lifespan conditions, industrialized bamboo solutions provide positive impacts on the environment by avoiding significant amounts of CO_2 emissions. Moreover, under these conditions, the potential income from CO_2 crediting is still significant, and its maximum can be achieved in early stages.

4.2 Electricity mix

The results from this analysis showed that the avoided CO_2 emissions from the recycling process contribute significantly to the results of the environmental impact and economic categories. These avoided emissions are directly connected to the electricity mix used on the country of study. In the case of the Philippines, the electricity mix is dominated by fossil fuels, so a significant amount of CO_2 credits can be obtained by avoiding these emissions. This sensitivity analysis considered a variation in the electricity mix that can occur in the future or the establishment of such a housing program on a different country. To test the consistency of the results an electricity mix with a share of 70% hydropower, similar to that found in countries such as Brazil or Colombia, was used. This analysis showed that a variation in the electricity mix significantly reduces the environmental and economic benefits, as shown in figure 6. This is due to the lower amount of CO_2 emissions that can be avoided from a "low CO_2 emitting" electricity mix. Nevertheless, even with this different electricity generation mix, positive environmental and economic benefits are still observed through the use of industrialized bamboo.

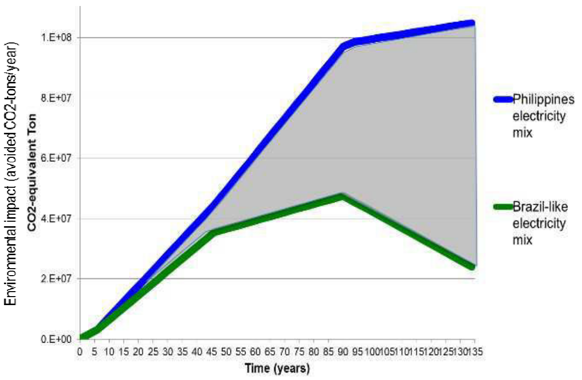

Figure 6 Sensitivity analysis of electricity mix

4.3 End-of-life scenarios

End-of-life scenarios have significant associated uncertainties because they represent future events that cannot be completely known. Thus, after the proposed housing unit's lifespan is reached, it is highly uncertain what will happen to the demolished materials. For this sensitivity analysis, two scenarios were considered: first, business as usual, in which the demolished construction materials are not used as fuel for the production of electricity. Thus, no avoided CO_2 emissions were considered in the environmental impact and economic categories. The second was the best case scenario, where the demolished construction materials are used as fuel for producing electricity. The results for glue-laminated bamboo were compared with those of glue-laminated wood and concrete hollow blocks and are presented in figure 7. From this figure, it is possible to see that changes in the end-of-life scenario produce a variation of 80% in the results for both glue-laminated bamboo and glue-laminated wood. The same occurs in the economic category, where a significant amount of CO_2 credits can be potentially obtained from the avoided emissions related to the end-of-life scenario. It is important to note that even under these conditions, both industrialized bamboo and wood perform better than concrete, as observed in figure 7. Furthermore, even if the avoided CO_2 emissions from the recycling of demolished construction materials are not considered, the industrialized bamboo solutions create environmental and economic benefits.

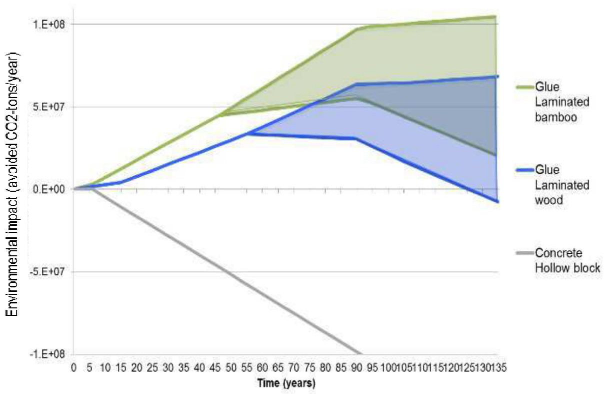

Figure 7 Sensitivity analysis of end-of-life scenarios

4.4 Sustainability Assessment

The results for the three sensitivity analyses were included in the sustainability assessment benchmark, as observed in figure 8. The results from the sensitivity analyses show a significant variation. Furthermore, it is possible to see that under certain conditions, the results for glue-laminated bamboo and glue-laminated wood overlap. The three studied construction materials are not affected on the social category by changes in the proposed variables. In all cases, the glue-laminated bamboo provides positive impacts across all categories. On the contrary, glue-laminated wood produces emissions when the end of life is not considered and when the electricity mix is changed.

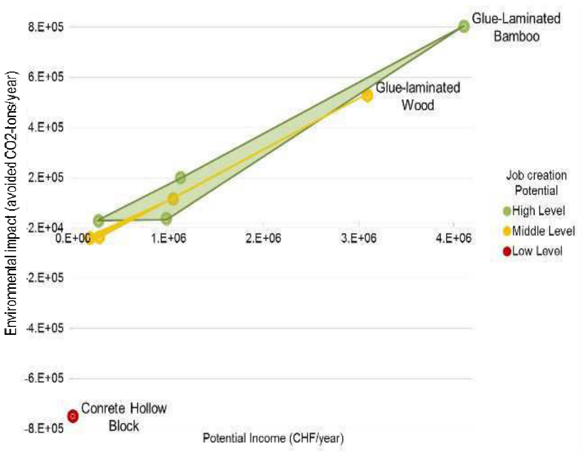

Figure 8 Sustainability assessment with sensitivity analysis

Under the proposed conditions and sensitivity analyses, glue-laminated bamboo always provides the most sustainable solution for housing. Figure 8 shows the potential that a bamboo-based housing program will produce positive impacts on the environment by reducing the levels of CO_2 and by providing extra income from CO_2 crediting that can be used in the financing of the housing units themselves.

5 CONCLUSIONS

This research assesses the sustainability of industrialized bamboo solutions for housing programs in the Philippines. The results and sensitivity analyses show that the use of industrialized bamboo in such programs can produce environmental, economic and social benefits. Over 28000 potential job positions can be created by the establishment of 5500 ha of managed bamboo plantations. These positions will be stable for the duration of the housing program and are only affected by the size of the program and its associated bamboo plantation. Thus, an increase on the number of planned housing units is associated with an increase in potential new jobs. Furthermore, the implementation of an industrialized bamboo-based housing program provides positive impacts on the environment by capturing and avoiding over 10^8 tons of CO_2equivalent of emissions over 130 years. Moreover, circa 490 million CHF can potentially be created over the same period with the crediting of temporarily stored and avoided CO_2 emissions associated with the used of industrialized bamboo solutions. From the sensitivity analyses, housing lifespan and national electricity generation mix are the most important factors that affect the results. Finally, it can be concluded that the use of industrialized bamboo solutions offers a sustainable approach for new housing construction. The associated positive impacts to the environment and the livelihood of communities engaged in such programs is directly related to the program size. Finally, the use of industrialized bamboo solutions for housing programs can support the regenerative development of the regions in which they are applied, leading to long-lasting improvements in their environment and livelihoods.

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7 REFERENCES

[AIS 2004] AIS; Colombian code for seismic design and construction, NSR-98. Seismic Engineering Colombian Association, Bogotá, Colombia, 2004.

[Archila-Santos, H. F. 2012] Archila-Santos, H. F., M. P. Ansell and P. Walker; Low Carbon Construction Using Guadua Bamboo in Colombia. Key Engineering Materials. 2012, **517**: 127-134,3037854359.

[De Flander, K. 2009] De Flander, K. and R. Rovers; One laminated bamboo-frame house per hectare per year. Construction and Building Materials. 2009, **23**(1): 210-218,0950-0618.

[Fearnside, P. M. 2002] Fearnside, P. M.; Why a 100-Year Time Horizon should be used for GlobalWarming Mitigation Calculations. Mitigation and Adaptation Strategies for Global Change. 2002, **7**(1): 19-30,1381-2386.

[Guha-Sapir, D. 2012] Guha-Sapir, D., F. Vos, R. Below and S. Ponserre; Annual Disaster Statistical Review 2011: The Numbers and Trends, published by the Centre for Research on the Epidemiology of Disasters (CRED) Brussels. 2012.

[Knoema 2015] Knoema; "Philippines - Population - Population growth rate (percent)." 2013, Retrieved 22.01.2015, 2015, from http://knoema.de/atlas/Philippinen/topics/Demographie/Bevölkerung/Bevölkerungswachstumsrate.

[Lang, C. 2015] Lang, C.; "How much does a carbon credit cost? "There is no such thing as a generic price," says ClimateCare's Edward Hanrahan." 2013, Retrieved 21.01.2015, 2015, from http://www.redd-monitor.org/2013/01/22/how-much-does-a-carbon-credit-cost/.

[Levasseur, A. 2012] Levasseur, A., P. Lesage, M. Margni, M. Brandão and R. Samson; Assessing temporary carbon sequestration and storage projects through land use, land-use change and forestry: comparison of dynamic life cycle assessment with ton-year approaches. Climatic change. 2012, **115**(3-4): 759-776,0165-0009.

[Mang, P. 2012] Mang, P. and B. Reed; Designing from place: a regenerative framework and methodology. Building Research & Information. 2012, **40**(1): 23-38,0961-3218.

[McCarthy, J. J. 2001] McCarthy, J. J.; Climate change 2001: impacts, adaptation, and vulnerability: contribution of Working Group II to the third assessment report of the Intergovernmental Panel on Climate Change, 2001, Cambridge University Press.

[Murphy, R. J. 2004] Murphy, R. J., D. Trujillo and X. Londoño; Life Cycle Assessment (LCA) of a Guadua House. International Symposium of bamboo -- Guadua, 2004, Pereira, Colombia

[Pedersen, M. 2009] Pedersen, M.; Towards a sustainable future: Adopting a regenerative approach to development. Ministry of Environment, New Zealand, 2009.

[Pre-Consultants 2012] Pre-Consultants; "SIMA Pro v7.3.3." 2012, from http://www.pre-sustainability.com/simapro-installation.

[Reed, B. 2007] Reed, B.; Shifting from ‘sustainability’to regeneration. Building Research & Information. 2007, **35**(6): 674-680,0961-3218.

[Riaño, N. M. 2002] Riaño, N. M., X. Londoño, Y. López and J. H. Gómez; Plant growth and biomass distribution on Guadua angustifolia Kunth in relation to ageing in the Valle del Cauca – Colombia. Bamboo Science and Culture. 2002, **16**(1): 43-51,ISSN 0197– 3789.

[Sánchez-Morales, R. 2011] Sánchez-Morales, R. and M. Leiva-Mora; Reforestation with bamboo as an ecological alternative on the sustainable production of construction materials and dwellings – Phase 2. Universidad Central “Marta Abreu” de Las Villas (UCLV), Cuba., Cuba, 2011.

[Swiss Centre for Life Cycle Inventories 2011] SCLCI; "EcoInvent Database." 2011, from http://www.ecoinvent.org.

[UNESCAP 2011] UNESCAP, U.; State of the Asian Cities Report 2011. UN Habitat, UN ESCAP, Bangkok, 2011.

[UNHabitat 2011] UNHabitat; State of the World´s Cities 2010/2011. UN Habitat Nairobi, 2011.

[Van der Lugt, P. 2009] Van der Lugt, P., J. Vogtländer and H. Brezet; Bamboo, a Sustainable Solution for Western Europe: Design Cases LCAs and Land-use, 2008, Centre for Indian Bamboo Resource and Technology.

[Van der Lugt, P. 2009] van der Lugt, P., J. Vogtländer and H. Brezet; Bamboo- a sustainable solution for Western Europe, Design Cases, LCA and Land-Use. Delft, 2009, INBAR International Network For Bamboo and Rattan, Technical University Delft.

[Vogtländer, J. G. 2013] Vogtländer, J. G., N. M. van der Velden and P. van der Lugt; Carbon sequestration in LCA, a proposal for a new approach based on the global carbon cycle; cases on wood and on bamboo. The International Journal of Life Cycle Assessment. 2013: 1-11,0948-3349.

[Wallbaum, H. 2012] Wallbaum, H., Y. Ostermeyer, C. Salzer and E. Zea Escamilla; Indicator based sustainability assessment tool for affordable housing construction technologies. Ecological Indicators. 2012.

[Wang, Z. 2009] Wang, Z., P. Shyam, X. Chen and L. Gao; Application of Bamboo-based Engineered Materials in Construction. International conference on modern bamboo structures, 2009, Bogotá, Colombia, Universidad de los Andes

[Xiao, Y. 2009] Xiao, Y.; Development of Prefabricated bamboo Earthquake Relief Shelter. International conferece of modern bamboo structures, 2009, Bogotá, Colombia, Universidad de los Andes

[Zea Escamilla, E. 2008] Zea Escamilla, E.; Design and application of laminated bamboo elements in frame construction and mechanical properties of laminated bamboo. MSc. Research, Wageningen University, 2008.

[Zea Escamilla, E. 2014] Zea Escamilla, E. and G. Habert; Environmental Impacts of Bamboo-based Construction Materials Representing Global Production Diversity. Journal of Cleaner Production. 2014, 0959-6526.

[Zea Escamilla, E. 2014] Zea Escamilla, E., G. Habert and L. F. Lopez Muñoz; Environmental Savings Potential from the Use of Bahareque (Mortar Cement Plastered Bamboo) in Switzerland. Key Engineering Materials. 2014, **600**: 21-33,3037859814