Scenario analysis of embodied energy and CO_2 emissions for multistory apartments in Indonesia

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Abstract. Contribution in the building sector to the global warming can be tackled by diminishing greenhouse gas (GHG) emissions (mainly CO_2) not only from operational energy but also from the embodied energy (EE) of construction materials. Harvested Wood Products (HWP) such as Cross Laminated Timber (CLT), Glued Laminated (Glulam) timber, among others, make multistorey wooden buildings possible. These wooden buildings could help to reduce EE and CO_2 emissions significantly. A material flow analysis (MFA) using an I-O (Input-Output) table was used to compare three scenarios for an 8-story apartment building in Indonesia (total floor area: 9140 m^2): First, the building had a reinforced concrete structure. Second, the building had a "hybrid" structure with reinforced concrete cores and first-floor elements, consisting of CLT floor panels, and Glulam columns and beams. Third, the building used only CLT panels besides reinforced concrete cores. The results showed that the last scenario achieved the largest CO_2 emissions and embodied energy reductions (58 t-CO_2 and 905 GJ), compared with the first scenario (81 t-CO_2 and 1110 GJ). Furthermore, we compare two methods to apply displacement factors (DF) to assess the CO_2 emissions savings for each CO_2 ton in wood products substituted in place of non-wooden products between the three building scenarios.

Keywords: Embodied Energy, Material Sustainability, Displacement Factor, Wood harvested products.

1 Introduction

Global warming and climate change are considered to be a consequence of greenhouse gas (GHG) emissions coming from several pollutants such as methane, nitrous oxide, perfluorocarbons, hydrofluorocarbons, sulphur hexafluoride, nitrogen trifluoride, and carbon dioxide (CO_2) [1]. CO_2 is the main contributor to such GHG emissions. In 2011, CO_2 was responsible for 86% of GHG emissions related to material production. Material production leads to 70% of GHG emissions coming from the construction sector when assessed by economic activity [2]. Thus, any effort in diminishing CO_2 emissions from the construction sector could play a major role in diminishing the whole of GHG emissions.

Buildings consume energy in all the phases of their life cycle, from design to construction, operation, and demolition. Embodied energy (EE), is the energy consumed in the extraction, production, processing, and transportation of the materials needed for building construction [3] and it accounts for 20% to 30% of the total energy consumed during a building's life cycle [4]. Material flow analysis (MFA) is a tool focused on the assessment of inputs and outputs (I-O) of materials in a particular building [5], useful when covering the construction (EE) phase of the building life cycle.

There are multiple methods to do an MFA some of them are: (1) Input–Output (I-O) approach where the inputs and outputs from macroeconomic Input-Output (I-O) tables, can be used to trace back the pollutants of every economic activity represented; (2) Process-based approach, where inputs and outputs are gathered directly on-site or using established databases; (3) Hybrid approach, where there is a mix of information between I-O table information and Process-based information [6].

Although the I-O approach could incur inaccuracies when it is needed to convert financial flows to physical quantities of materials, it offers a comprehensive way to cover the boundary system upstream of the main processes. It is a good approach to follow when process-based data is not easily available and used by many researchers, thus, the Embodied energy (EE) and CO_2-eq were calculated with an I-O approach. Then, the results were further analyzed by applying displacement factors (DF), used by many researchers to assess the

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environmental performance between several building material scenarios [7].

DF is a proportional assessment approach, which shows the benefits in terms of saved CO_2 Tons derived from the use of one material application over another. Sathre and O'Connor [8] developed mathematical equations to apply in different building scenarios. Later Leturcq [9] questioned the simplicity of the initially proposed DF and used more variables for a more precise application. DF has been readily used to compare the smaller CO_2 emissions and EE from the use of new HWP used as structural building materials over "traditional" more emissive materials such as reinforced concrete [10]. Leskinen et al [7] made an extensive review of 51 studies, that provided 433 different DFs. Myllyviita et al [11], reviewed 37 journal articles, that provided 149 different DFs, finding that most of the DF application was related to the construction sector (55 DFs out of 149). These studies stressed the need for DF to include the product demand and production variations over time, which would have a direct influence when comparing the environmental impact of one determinate building material scenario over other. The studies analyzed in both studies, generally reported positive values for the DF, providing contextual support to the idea that the use of more HWP in substitution of non-wooden materials would contribute to diminishing GHG emissions, especially CO_2 emissions.

The use of HWP for structural application in building construction offers the possibility to reduce the EE and CO_2 emissions of the built environment. A material with the capacity to absorb CO_2 even after being processed and used as a building element, wood offers better environmental performance than other usual structural materials such as concrete or steel, with a far less GHG emissive production process. This is especially important if seen from the perspective of effective material substitution [6], where HWP is used as structural building components, a function for which HWP was not typically used.

An I-O MFA using Indonesian National Level Input Output Table was conducted to compare the *initial* EE and CO_2 emissions of three structural material scenarios for a residential building (Rusunami). From the data product of that I-O MFA, this study applies different approaches for DF for CO_2 emissions among the structural material scenarios proposed.

The objective of this research is to assess the amount of saved CO_2 emissions derived from the substitution of new structural construction systems developed from HWP for non-wooden structural building components among different building scenarios. Two different DF methods would be applied to the amounts of CO_2 emissions resulting from an I-O MFA. By such application, this study provides a pathway for the application of DF in the assessment of CO_2 emissions among different structural material scenarios for Rusunami buildings in Indonesia.

To achieve these objectives, Section 2 "Case study building", explores the basic Rusunami building design, and it creates building material scenarios for I-O MFA and DF applications. Section 3 "Methodology and assumptions" gives details of all the equations used for the calculation of CO_2 emissions and GJ of EE using I-O tables. The methodology for DF calculation is also explained in this section, and furthermore, effective substitution and assumptions are explained in detail. Section 4 "Results and discussion" discusses the findings and results of the study by calculating the CO_2 emissions and EE for all scenarios. Section 5 indicates the results from the application of DF to the different building scenarios. Finally, section 6 draws conclusions, identifies limitations, and proposes future research.

2 Case study building

2.1 Building design

An analysis of 268 apartment buildings was performed in Indonesia, where 220 of them were privately funded developments for upper-middle households called condominiums, while 48 of them were public-funded, government housing developments for low-income households called Rusunami.

Fig. 1 shows, the most common apartment design types for Rusunami buildings, being two-bedroom apartments with one bathroom and one-bedroom apartments.

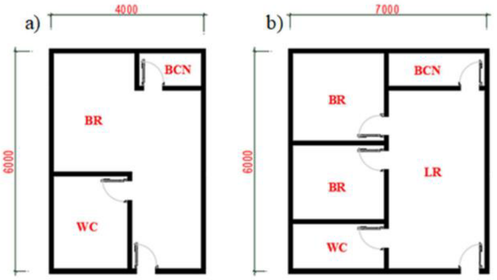

Fig. 1. Most representative apartment types from 268 housing complexes in Indonesia.

The main characteristics of the building that would serve as the base of analysis for this study were determined in terms of typology, apartment type to be used, and total area. An 8-story, double loaded corridor typology building, with an area of 9140 m^2 would be a good representative case of Rusunami. Regarding the height, according to Indonesian national building regulation 21 of 2021, every building of 8 stories or higher is considered a high-rise building, thus, the scenario comparison was among high-rise housing buildings. A typical floor plan for the case study building was developed by mixing the two most recurrent apartment types as shown in Fig. 2.

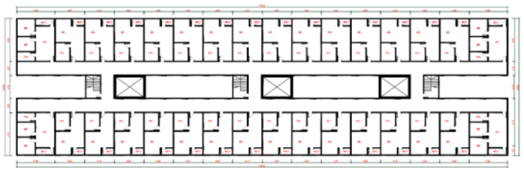

Fig. 2. Typical floor plan of Rusunami apartment used for analysis.

2.2 Building Scenarios

Three structural material scenarios were proposed for analyzing the 8-story Rusunami building with 9140 m^2 of total floor area. In all cases, roof elements were omitted, focusing on the main structural elements.

Fig. 3 shows the different material scenarios developed: (1) Scenario 1 is a fully reinforced concrete structure. (2) Scenario 2 is a hybrid building, where the columns and beams on the first floor and the elevator and stairs shafts are made of reinforced concrete. The columns and beams from the 2nd floor onwards are made of glulam and the floors, are made from cross-laminated timber (CLT). (3) Scenario 3 is a hybrid building as well, but only the elevator and stairs shafts remain made of reinforced concrete. There is no glulam, and the floors and walls are made of CLT panels.

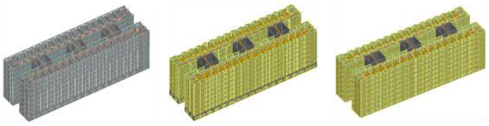
Scenario 1 Scenario 2 Scenario 3

Fig. 3. Concept model of different building scenarios.

3 Methodology and assumptions

3.1 MFA Calculations

After the design of the three building scenarios was completed, a bill of quantities (BOQ) was taken out from them, then, the material quantity is divided by the floor area using the following equation:

$$Q=V*D/F \qquad (1)$$

Where Q is the material quantity per 1m^2 of the floor (kg/m^2); V is the volume of building materials (m^3); D is the density of building materials, and F is the total area of the building (m^2).

Table 2 shows the material intensity (kg/m^2) for every building scenario.

Table 2. Material intensity by every building scenario.

Material	Scenario 1 (kg/m^2)	Scenario 2 (kg/m^2)	Scenario 3 (kg/m^2)
Cement	245	28	14
Sand	432	52	29
Gravel	415	75	39
Steel	57	9	4
Gypsum	10	66	3
Paint	7	1	0
Ceramic	25	3	3
Glass	1	1	1
Aluminium	1	1	1
Wood	5	318	352

Given that the materials used have different measurement units, it is necessary to convert them to the right unit using the next equation:

$$U=q*c \qquad (2)$$

Where U is the material unit corresponding with the market's prices; q is the material quantity in m^2 or m^3; and c is the conversion coefficient (please consult the Guideline of Building construction material and civil engineering, Part IV: Unit of work price analysis for housing in Indonesia) [12].

Since the intensity of materials is measured in Million Indonesian Rupiah (MIDR), a calculation of material quantity per every MIDR was also needed. It was solved with the following equation:

$$Qi= q/ 1,000,000\ IDR \qquad (3)$$

Where Qi is the material quantity per million Indonesian Rupiah (MIDR) (unit/MIDR) and q is the material quantity (unit).

After this, it is necessary to multiply the GJ/MIDR and CO_2-eq/MIDR coefficients of the corresponding economic sector of the economy of every building material to obtain the GJ (Gigajoules) of EE and tonne-CO_2-e/tonne of emissions from the materials used in the project respectively.

A Leontief matrix was used from the I-O tables of the Indonesian national level to calculate the domestic and imported coefficients of EE and CO_2 emissions of the materials used in the building scenarios.

The following are the equations for the calculation of EE used in the analysis:

Domestic EE:

$$E_{dm} = \sum_{k}^{n} \left[\left(\frac{e_{dm}}{m} \cdot (I-(I-M)\cdot A)^{-1} \right)_{k} \cdot U_k \right] \qquad (4)$$

Imported EE:

$$E_{im} = \sum_{k}^{n} \left[\left(\frac{e_{im} \cdot (I-A)^{-1}}{m} \right)_{k} \cdot U_k \right] \qquad (5)$$

Total EE:

$$E = \sum_{k}^{n} (E_{dm} + E_{im}) \qquad (6)$$

Where E is the EE of building material (GJ); E_{dm} is the domestic EE of building material; E_{im} is the imported EE of building material; e_{dm} and e_{im} are the direct energy consumption of building material (GJ/MIDR); I is the identity matrix; A the input coefficient matrix; M the Import matrix; $(I-(I-M) A)^{-1}$ is the domestic Leontief inverse matrix of building material;· $(I-A)^{-1}$ is the imported Leontief inverse matrix of building material; U_k is the unit of building material k, and m the material intensity of the building material (unit of material/MIDR).

CO_2-eq is usually measured in a mass unit. In the case of this study, it was measured in tonne (1000 kg) of CO_2 (tonne-CO_2-e/tonne) embodied in the building materials. The following are the equations for the calculation of CO_2-eq used in the analysis:

Domestic CO_2-eq:

$$ECO_{2dm} = \sum_{k}^{n} \left[\left(\frac{e_{CO_2dm} \cdot (I-(I-M)\cdot A)^{-1}}{m} \right)_{k} \cdot U_k \right] \qquad (7)$$

Imported CO_2-eq:

$$ECO_{2im} = \sum_{k}^{n} \left[\left(\frac{e_{CO_2im} \cdot (I-A)^{-1}}{m} \right)_{k} \cdot U_k \right] \qquad (8)$$

Total, CO_2-eq:

$$ECO_2 = \sum_k^n (ECO_{2dm} + ECO_{2im}) \quad (9)$$

Where E is the embodied CO_2 of building material (ton CO_2-eq); ECO_{2dm} is the domestic embodied CO_2 of building material (ton CO_2-eq); ECO_{2im} is the imported embodied CO_2 of building material (ton CO_2-eq); e_{CO2dm} and e_{CO2im} are the direct CO_2 emission of building material (ton CO_2-eq /MIDR).

3.2 DF calculation equations

DF equations were applied to the resulting quantities of EE and CO_2 emissions of the three building scenarios to assess the CO_2 emissions saved from the use of alternative wooden structural building systems. Scenario 1 was compared against Scenario 2 and later, compared against Scenario 3.

DF is defined by the following equation, derived from Sathre and O'Connor approach, and cited by Leturcq [9]:

$$DF = (|f_{nw}| - |f_w|)/C_w \quad (10)$$

Where f_{nw} is the use of non-wood options; f_w is the Greenhouse emissions from the use of wood options, and C_w is the carbon mass content of the wood product

Sathre and O'Connor's approach has been used in several studies and specialized literature [13] after its publication.

Leturcq [9] points out critical assumptions from the previous approach, like that the forest where the wood comes from absorbs the same quantity or more CO_2 than it is released to the atmosphere from organic matter decomposition and combustion or decomposition of the harvested wood, which is very rare and could happen only in very special cases.

The former approach assumes that conditions such as soil fertility, forestry management, and tree species, among others, remain the same in time, which does not happen usually. Also, the reduction or increase in CO_2 emissions is related to the variations of non-wooden and wooden products annually, thus, displacement factors should be applied in the variation of production and not in the product itself and in the production of materials where HWP makes an effective substitution, this means, where it has not been used before or usually.

DF is redefined by Leturcq [9] using the following equation:

$$DF = -\Delta|E|/\Delta N_w = |f_{nw}| - |f_w| - |f_{nw}|\Delta N/\Delta N_w \quad (11)$$

Where $\Delta|E|$ is the Negative variation in the GHG emissions of wooden and non-wooden products; ΔN_w is the variation in the production of wooden products; f_{nw} is the use of non-wood options; f_w is the Greenhouse emissions from the use of wood options; and ΔN the variation in the production of wooden and not-wooden products.

3.3 Effective substitution and assumptions

From the detailed analysis of the quantities from the analysis it is possible to identify three material trends: materials whose quantities drop through scenarios; materials that remain unchanged through scenarios; and wood and steel, in which CO_2 emissions invert between scenarios, proving effective substitution in the structural materials in terms of CO_2 emissions reduction.

Both equations are applied first, between scenarios, and secondly, between steel and wood, materials with effective CO_2 emission substitution.

The application of the second equation considers the negative variation in the GHG emissions of wooden and not wooden products, as well as the variation in the production of wooden and non-wooden products.

A negative variation of -150 m^3 was assumed for the wooden products manufactured annually, while for the number of produced items, wooden or not, a negative variation of -250 m^3 was assumed.

4 Results and discussion

The results of the I-O MFA show that the use of structural wooden elements contributes to diminishing the CO_2 emissions and the *initial* EE of building construction, specifically, residential Rusunami buildings in Indonesia.

Fig. 4 shows the amount of CO_2 emissions in tonne-$CO_{2\text{-}e}$/tonne for every material in every building scenario. The scenario with the lowest amount of CO_2 emissions was scenario 3 with 58 tonne-$CO_{2\text{-}e}$/tonne. CO_2 emissions of scenarios 1 and 2 were 81 tonne-$CO_{2\text{-}e}$/tonne and 63 tonne-$CO_{2\text{-}e}$/tonne respectively. The number of structural components from HWP in scenarios 2 & 3 is directly related to their decreasing CO_2 emissions numbers when compared to scenario 1. The more HWPs are used as structural elements, the lower the CO_2 emissions. In scenario 1, the materials contributing to the most CO_2 emissions are those related to reinforced concrete production: cement, sand, gravel, and steel. Paint also contributed to high amounts of CO_2 emissions in scenario 1. In contrast, steel and wood are the major contributors to CO_2 emissions in both scenarios 2 and 3. Gypsum contributed importantly to the CO_2 emissions of scenario 2.

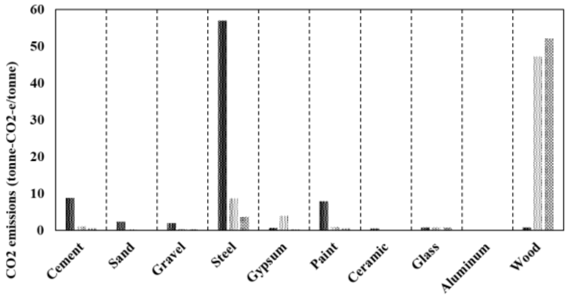

Fig. 4. Amount of CO_2 emissions (tonne $CO_{2\text{-}e}$/tonne) for every material in every building scenario.

Fig. 5 shows the amount of EE in GJ for every material in every building scenario. Just like with CO_2 emissions, the scenario with the lowest amount of GJ of EE was scenario 3 with 905 GJ. GJ of EE for scenarios 1 and 2 were 1110 GJ and 968 GJ respectively. Also, like with CO_2 emissions, the number of structural components from HWP in scenarios 2 & 3 is directly related to their decreasing EE numbers when compared to scenario 1. The more HWPs are used as structural elements, the lower the EE. When assessing EE by the material the behavior was the same as with CO_2 emissions, with the materials having the biggest share of EE shifting among scenarios.

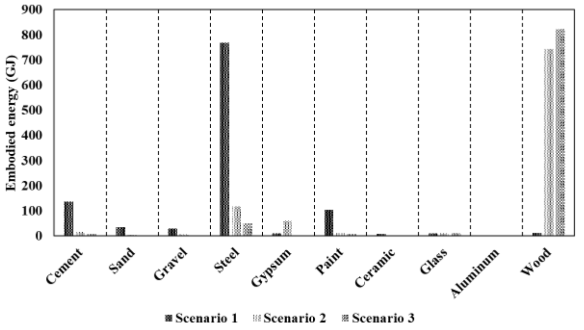

Fig. 5. Amount of EE (GJ) for every material in every building scenario.

Fig 6 reinforces the hypothesis of past figures in the decreasing CO_2 emissions in tonne-$CO_{2\text{-}e}$/tonne directly related to a higher proportion of HWPs used as structural building components. The biggest decrease occurs between scenarios 1 and 2, being the direct comparison between common reinforced concrete structures and HWP structural systems. As scenarios 2 and 3 both use HWP structural systems, the decrease in CO_2 among them is smaller.

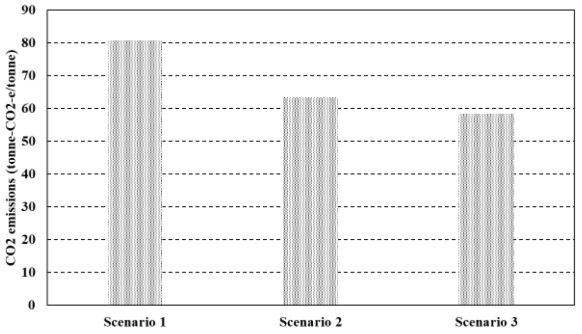

Fig. 6. Total CO_2 emissions (tonne-$CO_{2\text{-}e}$/tonne) of every building scenario.

Like with CO_2 emissions, Fig 7 also shows the biggest decrease of EE between scenarios 1 and 2, being the direct comparison between common reinforced concrete structures and HWP structural systems. Similar to CO_2 emissions, the decrease in EE between scenarios 2 and 3 is smaller, as they both use HWP structural systems.

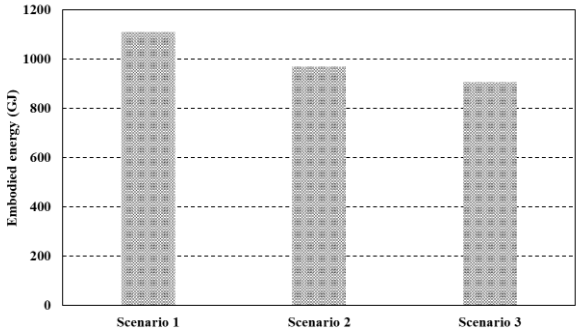

Fig. 7. Total EE (GJ) of every building scenario assessed

According to Fig. 4 and Fig. 5, there is an effective substitution of the EE and CO_2 emissions between scenarios 1 and 2 and scenarios 1 and 3. The embodied energy and CO_2 emissions from a resource-intensive material such as the steel for the reinforced concrete in Scenario 1 are replaced by the CO_2 emissions and EE of wood in scenarios 2 and 3.

5 Displacement factor application

With the EE and CO_2 emissions quantities for every scenario, it is possible to apply the DF among the three building scenarios. The application of DF uses equations (10) and (11) and compares, first, the total amount of materials between scenarios and after that, the materials with effective substitution (Steel and wood).

5.1 Application of DF as defined by equation (10) from the approach of Sathre and O'Connor.

Table 3 shows the details of DF application among building scenarios when comparing all their materials. In this case, the highest DF was 0.014, when comparing scenario 1 vs scenario 3. This DF means that for each tonne-$CO_{2\text{-}e}$/tonne in wood products substituted in place of non-wooden products, there occurs an average GHG emission reduction of approximately 0,014 tonne-$CO_{2\text{-}e}$/tonne.

Using this approach, the highest GHG emission savings (0,969tonne-$CO_{2\text{-}e}$/tonne) also came from the comparison between scenario 1 vs scenario 3.

Table 3. DF derived from Sathre and O'Connor applied in all the materials of the building scenarios.

Displacement factor	**SC1 vs SC2**	**SC1 vs SC3**
GHG emissions resulting from the use of non-wooden materials (tonne-$CO_{2\text{-}e}$/tonne)	80.73	80.73
GHG emissions resulting from the use of wooden materials (tonne-$CO_{2\text{-}e}$/tonne)	63.38	58.35
Wood mass tonne-$CO_{2\text{-}e}$/tonne content	1455.38	1606.57

Displacement factor tonne-CO_{2-e}/tonne	**0.012**	**0.014**
Average GHG emissions resulting from both scenarios tonne-CO_{2-e}/tonne	**72.05**	**69.53**
Average tonne-CO_{2-e}/tonne Savings	**0.859**	**0.969**

Table 4 shows the details of DF application among building scenarios when comparing only the materials having an effective substitution (wood and steel). Unlike the comparison between all the materials of building scenarios, the highest DF was 0.007, when comparing scenario 1 vs scenario 2. This DF means that for each tonne-CO_{2-e}/tonne in wood products substituted in place of non-wooden products, there occurs an average GHG emission reduction of approximately 0.007 tonne-CO_{2-e}/tonne.

Using this approach, the highest GHG emission savings (0.35tonne-CO_{2-e}/tonne) also came from the comparison between scenario 1 vs scenario 2.

Table 4. DF derived from Sathre, and O'Connor applied to the materials having an effective substitution (Wood and steel) among the building scenarios.

Displacement factor	**SC1 vs SC2**	**SC1 vs SC3**
GHG emissions resulting from the use of non-wooden materials (tonne-CO_2-e/tonne)	57.05	57.05
GHG emissions resulting from the use of wooden materials (tonne-CO_2-e/tonne)	47.28	52.19
Wood mass tonne-CO_2-e/tonne content	1455.38	1606.57
Displacement factor tonne-CO_2-e/tonne	**0.007**	**0.003**
Average GHG emissions resulting from both scenarios tonne-CO_2-e/tonne	**52.16**	**54.62**
Average tonne-CO_2-e/tonne Savings	**0.35**	**0.165**

Fig. 8 shows the average CO_2 emission savings when applying DF as defined by the equation derived from Sathre and O'Connor (10) among building structural material scenarios. Following this approach, the highest CO_2 emission savings came from the comparison between all the materials of building scenarios.

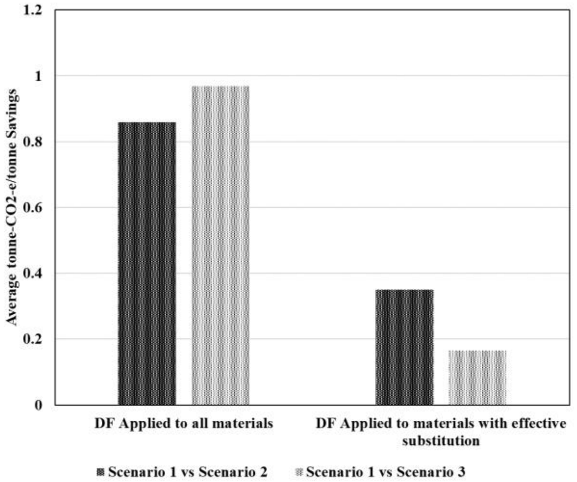

Fig. 8. Average CO_2 emission savings when applying DF defined by the equation derived from Sathre and O'Connor (10) among building scenarios.

5.2 Application of DF as defined by equation (11) proposed by Leturcq.

Table 5 shows the details of DF application among building scenarios when comparing all their materials. In this case, the highest DF was 0.02, when comparing scenario 1 vs scenario 2. This DF means that for each tonne-CO_{2-e}/tonne in wood products substituted in place of non-wooden products, there occurs an average GHG emission reduction of approximately 0.02 tonne-CO_{2-e}/tonne.

Using this approach, the highest GHG emission savings (1.41 tonne-CO_{2-e}/tonne) also came from the comparison between scenario 1 vs scenario 2.

Table 5. Leturcq's DF was applied to all the materials of the building scenarios.

Displacement factor	**SC1 vs SC2**	**SC1 vs SC3**
GHG emissions resulting from the use of non-wooden materials (tonne-CO_2-e/tonne)	80.73	80.73
GHG emissions resulting from the use of wooden materials (tonne-CO_2-e/tonne)	63.38	58.35
Displacement factor tonne-CO_2-e/tonne	**0.020**	**0.010**
Average GHG emissions resulting from both scenarios tonne-CO_2-e/tonne	**75.05**	**69.53**
Average tonne-CO_2-e/tonne Savings	**1.419**	**0.711**

Table 6 shows the details of DF application among building scenarios when comparing only the materials having an effective substitution (wood and steel). Unlike the comparison between all the materials of building scenarios, the highest DF was when comparing scenario 1 vs scenario 3. In this case, for each tonne-$CO_{2\text{-e}}$/tonne in wood products substituted in place of non-wooden products, there occurs an average GHG emission reduction of approximately 0.02 tonne-$CO_{2\text{-e}}$/tonne.

Using this approach, the highest GHG emission savings (1.04 tonne-$CO_{2\text{-e}}$/tonne) also came from the comparison between scenario 1 vs scenario 3.

Table 6. Leturcq's DF applied to the materials having an effective substitution (Wood and steel) among the building scenarios.

Displacement factor	**SC1 vs SC2**	**SC1 vs SC3**
GHG emissions resulting from the use of non-wooden materials (tonne-CO_2-e/tonne)	57.05	57.05
GHG emissions resulting from the use of wooden materials (tonne-CO_2-e/tonne)	47.28	52.19
Displacement factor tonne-CO_2-e/tonne	**0.019**	**0.019**
Average GHG emissions resulting from both scenarios tonne-CO_2-e/tonne	**52.16**	**54.62**
Average tonne-CO_2-e/tonne Savings	**0.996**	**1.043**

Fig. 9 shows the average CO_2 emission savings when applying DF as defined by the equation proposed by Leturcq (11) among building structural material scenarios. Like in the use of DF as defined by equation (10), the highest CO_2 emission savings came from the comparison between all the materials of building scenarios.

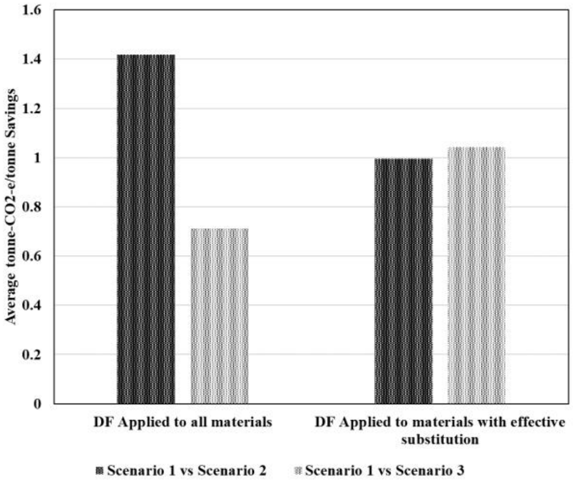

Fig. 9. Average CO_2 emission savings when applying DF defined by Leturcq's equation (11) among building scenarios.

6 Conclusions

Through this study, we have shared some examples of displacement factor application among material options to choose the one that represents the highest CO_2Ton emission reductions. The use of wood over concrete and steel for structural building purposes is a good example of effective material substitution than can help reduce the CO_2Ton emissions and EE of the built environment.

Further improvement in the application and accuracy of displacement factors could be achieved by broadening the system boundaries of the I-O MFA that serves as the base for the information used in the analysis. The I-O MFA from which data comes could also include more building life phases beyond the provision of construction materials to the construction site. The main components of the carbon stock exchange of the forest could be considered in the future, such as the carbon content of harvested wood, decomposition of harvested residues, forest regeneration, or evolution in time of the impact of harvesting.

For the use of equation (11) the figures of negative variation of wooden and non-wooden products manufactured annually could be potentially replaced by IOT information and other economic data that can provide more certainty over the demand of a determinate product within the transactions of the economy.

The application of DF among different building scenarios shows effective savings in CO_2 emissions when using alternative HWP structural materials over more common reinforced concrete structures.

The study also showed the highly emissive nature of steel. Although the amount of material was the smallest from the mix necessary to produce reinforced concrete (together with cement, sand, and gravel), steel reported the highest CO_2 emissions and GJ of EE of the mix, playing an important role in the wood substitution reflected in positive DF in scenarios 2 and 3.

The main limitations of this study are the boundary system of the I-O MFA, and the assumptions made for the variations of HWP and non-wooden products.

Further research could include process-based information to apply a hybrid MFA as a base for analysis and further study of economic data could bring more certainty on the assumptions used in equation (11) when applying more detailed DF.

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