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# INFLUENCE OF DIFFERENT END-OF-LIFE CYCLE SCENARIOS ON THE ENVIRONMENTAL IMPACTS OF TIMBER-CONCRETE COMPOSITE FLOOR SYSTEMS

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**ABSTRACT:** Timber-concrete composite (TCC) floor systems attracted attention in the construction industry because of their low environmental impacts while demonstrating decent load-bearing capacity. However, the environmental impacts of possible end-of-life scenarios of TCC floors have not been extensively studied. To address this gap, a comprehensive life cycle assessment (LCA) study was conducted on three different slabs: a Reinforced concrete slab, a Steel concrete composite slab, and a CLT-concrete composite slab. The study revealed that the CLT-concrete composite slab has the lowest Global Warming Potential (GWP) among the three slabs. Subsequently, a more detailed LCA is performed on the CLT-concrete composite slab considering three different end-of-life scenarios of the CLT: 1. Energy recovery via incineration, 2. The prevailing scenario in Europe (a combination of energy recovery, recycling, and disposal), and 3. Reuse. The results show all three scenarios are beneficial in terms of GWP whereas the 3rd scenario is the most beneficial one.

**KEYWORDS:** Timber-concrete composite floor system, Life cycle assessment, Environmental impact, Reusable slab

## 1 INTRODUCTION

The construction industry is a major consumer of global resources and contributes greatly to waste generation and greenhouse gas emissions [1, 2]. In the last few decades, with the aim to reduce the environmental impacts of the construction industry, the use of renewable and more environmentally friendly materials such as timber and engineered wood products have gained more attention due to their green properties such as low carbon footprint and low embodied energy. Previous studies have shown that Timber-Concrete Composite (TCC) floor systems are promising sustainable solutions since they have decent structural behavior while having low environmental impacts [3].

TCC slabs have several advantages over conventional Reinforced Concrete (RC) slabs. By replacing concrete with timber, the environmental impacts of the floor system can be reduced about 30 to 50 percent [4]. Moreover, TCC can be used for resource-saving and lightweight constructions. These advantages can be expanded if the TCC slabs are designed to ensure the concrete is only subjected to compression and that all or most of the timber is stressed in tension. Consequently, TCC slabs should be designed so that shear between the timber and concrete components is transferred effectively through a proper shear connector system. The degree of composite action of the slab depends on the efficiency of the shear transfer system between the two materials. Furthermore, the connection system influences the sustainability of the TCC slab since it manipulates the fabrication, installation, maintenance, and End-of-Life (EoL) scenario. Hence, important aspects of sustainability such as prefabrication, deconstruction, recycling, and reuse must be considered during the design of the shear connection. A shear connection system that bonds the two materials permanently makes the deconstruction, reuse, or recycling difficult while a demountable shear connection facilitates these processes. This encouraged researchers to develop new shear connections suitable for prefabrication [5–7] and deconstruction [8, 9]. Having these new solutions which facilitate the recycling and reuse of TCC slabs, it is important to evaluate and compare the environmental impact of different EoL cycle possibilities for TCC floor systems.

This paper aims to study the environmental impacts of different floor systems for identical loading and span length. Then, a comparison between different EoL scenarios for the timber used in TCC floors is studied to identify the best solution considering the environmental impacts.

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## 2 ASSESSMENT OF THE ENVIRONMENTAL IMPACT

Life-Cycle Assessment (LCA) is a common method that is used for the analysis of the environmental impact of products [10]. It is an analysis technique that evaluates the environmental impacts of different stages of a designed product during its life cycle. In an LCA study, an inventory of the energy and materials which are used for the product is determined and the corresponding potential environmental impacts are calculated to improve the environmental profile of a product or compare it to another one.

Many studies evaluate the environmental impacts, considering the Global Warming Potential (GWP) and Primary Energy (PE), for some or all of the life cycle stages of a designed product [11]. GWP is a metric to quantify the total global warming effect of a substance over a specified time horizon. The GWP of a substance is defined as the ratio of the cumulative radiative forcing over a specified life cycle stage due to the emission of a unit mass of a substance, relative to the equivalent emissions of $CO_2$. PE states to the energy that is first extracted from natural sources and then used to generate electricity, heat, or power for other purposes. The sources of primary energy include renewable energy sources such as wind, solar, hydro, and geothermal, as well as non-renewable energy like coal, oil, and natural gas [12]. For construction materials and components, the stages which are mostly considered are Production and Construction (A), Use(B), End of Life (C), and Benefits and Loads (D) [13]. The considered stages in this study are demonstrated in Figure 1 which are the most relevant ones to the floor systems.

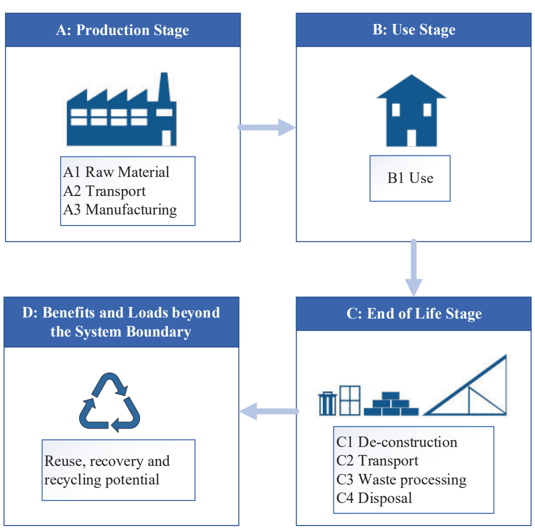


***Figure 1:*** *Lifecycle stages of construction materials and components. Based on [13]*

Stage A includes the extraction and processing of the raw materials, as well as their transportation to the manufactory where the floor component is produced. The construction process stage is not considered here because it does not have a noticeable influence compared to the other stages on a component level of analysis. Stage B only considers the use phase, assuming that the floor systems will not require any maintenance, repair, replacement, refurbishment, energy, or water during their service life. Stage C includes the deconstruction of the component, transportation, waste processing, and disposal. Stage D depends on the method that is used to derive benefits from the materials or components through reuse, recovery, or recycling. Although all the stages influence the environmental impacts of construction materials, stages A, C, and D are the decisive ones since stage B has no or a very small contribution to the environmental impacts.

Depending on the scope of an LCA analysis, different stages are considered in a study. A cradle-to-grave (CTG) scope considers stages A, B, and C, whereas a cradle-to-cradle (CTC) scope includes stages A, B, C, and D. The CTG approach examines the environmental impacts of a product from the extraction of raw materials to its disposal. On the other hand, the CTC approach takes into account the possibility of reusing, recovering or recycling the materials and components of the product at the end of its life. This approach considers the grave of a structure as the new cradle for its materials and components, enabling them to be used again in the manufacturing process of new products, reducing waste and the need for additional raw materials.

## 3 ASSESSMENT OF DIFFERENT FLOOR SYSTEMS

The Eco-Construction for Sustainable Development (ECON4SD) project at the University of Luxembourg has the objective of advancing toward a sustainable and circular society. This initiative aims to accomplish this goal by developing innovative architectural and structural design models that are resource and energy-efficient. The underlying purpose of this project is to create constructions that utilize sustainable practices, thereby minimizing their environmental impact. This paper study the environmental impacts of different possible floor systems to find a suitable floor system for the prototype 3 building in the ECON4SD project [14], which is a demountable building made of standard prefabricated modules. Each module has a length of 10.8 meters, a width of 10.8 meters, and a height of 3 meters. The building is made by adding these modules and expanding the building horizontally and vertically as it is shown in Figure 2. The architectural concept is designed for adaptive usage over the life cycle such as residential, office, and public buildings. After each lifecycle, the building can be modified for a new purpose or can be demounted and reused in another building site.

To find a suitable floor system for this prototype building, 3 different floor systems are designed statically. Then, the environmental impacts of the floor systems are compared through a cradle-to-grave LCA analysis. The proposed floor systems are Reinforced Concrete (RC), Steel-


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Concrete Composite (SCC), and Timber-Concrete Composite (TCC). The floor systems which are depicted in Figure 3, are designed for an office building loading condition and a 10.8 meters single-span system. The design considers both load-bearing capacity and serviceability of the floor for a lifespan of 50 years. Since the building is meant for prefabrication and demounting, floor modules are designed as prefabricated slabs with 1.8 meters in width.

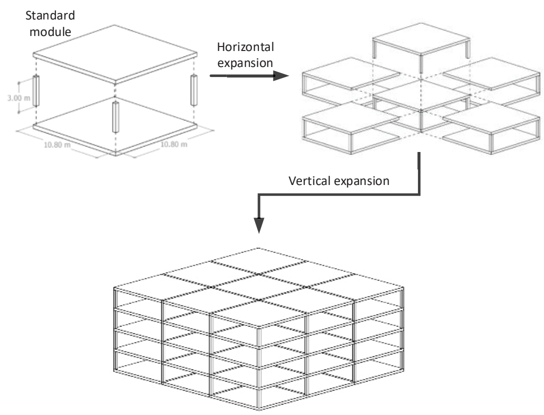


***Figure 2:*** *Architectural concept and standard module expansion for ECON4SD building prototype 3. From: [14]*

The TCC slab includes a 60 mm deep concrete slab on top of a Cross-Laminated Timber (CLT) panel with a thickness of 300 mm. CLT is a type of engineered wood product that is made from layers of solid-sawn lumber and is used in construction as floors, walls, roofs, etc. The layers are stacked in alternating orthogonal directions and then glued together under pressure to form a solid, stable panel. The CLT and concrete are connected by shear connections. The SCC slab is made of an IPE 360 steel profile with a 65 mm deep concrete slab. The RC floor has the highest thickness of 440 mm and The TCC has the lowest thickness of 360 mm.

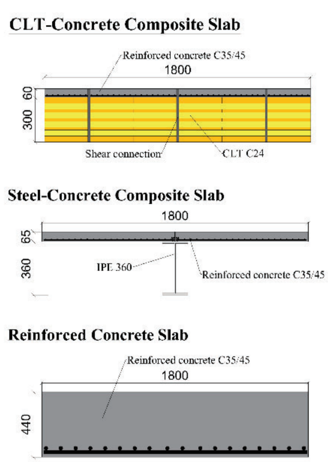


***Figure 3:*** *The investigated floor systems (dimensions in mm).*

Based on the designed floor systems, all material quantities required for each slab module are calculated. Then, the ÖKOBAUDAT German database [15] which provides data on the environmental impacts of the construction products, is used to calculate the GWP and PE of all the materials in each stage except for CLT whose environmental impact is extracted from Stora Enso environmental product declaration [16]. Figure 4 and Figure 5 show the results of the LCA analysis in GWP and PE, respectively. For each floor system, the results are calculated for all stages and the total CTG is presented. The GWP results for the TCC and SCC floors are similar with a small advantage for the TCC slab while the result for the RC slab is about 3 times higher than the other two floors. This is due to the high $CO_2$ footprint of cement in the production stage. For TCC, the production stage of timber contributes to removing $CO_2$ from the environment while the EoL stage releases $CO_2$ back into the environment due to incineration. Since the steel in the SCC slab will be recycled in stage C, the $CO_2$ contribution comes mostly from the production stage. Stage B contribution for all the slabs is negligible since it counts only the insignificant recovered $CO_2$ by concrete carbonation during the utilization stage.

The results for PE are different since the SCC slab requires about 30% less energy compared to the TCC slab. Yet, the RC slab requires the highest PE with about 2 times more than the TCC slab. The majority of the demanded PE is used in the production stage for all of the slabs. Only for the TCC slab, there is recovered PE which belongs to the heat recovery of the timber by incineration in stage C. Figure 5 also demonstrates the proportion of the renewable and non-renewable energy. Although the TCC slab requires more primary energy, it is mostly acquired from renewable energy. This is contrary to the SCC slab. Therefore, one can claim that the TCC slab is more sustainable compared to the other two slabs in a cradle-to-grave LCA analysis.

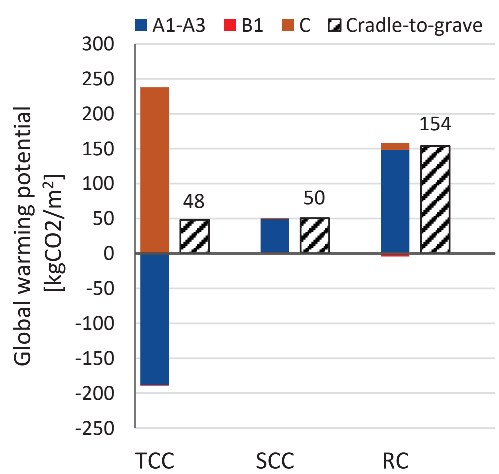


***Figure 4:*** *CTG global warming potentials of TCC, SCC, and RC slabs*

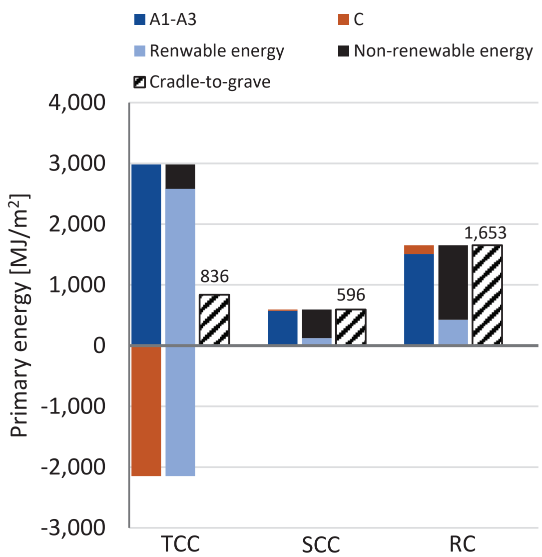


***Figure 5:*** *CTG primary energy of TCC, CLT, and RC slabs*

To have a cradle-to-cradle LCA, the potential GWP and PE relevant to stage D of each slab are calculated to determine the loads and benefits of each substance from its reuse, recycling, or recovery. For both GWP and PE measures, as it is shown in Figure 6 and Figure 7, respectively, the TCC slab stands significantly more beneficial than the other two slabs. For GWP this goes from 6 times compared to the RC slab up to 12 times better compared to the SCC slab. For PE the same trend exists when comparing TCC with RC and SCC slabs with 18 times and 53 times more recovered energy, respectively.

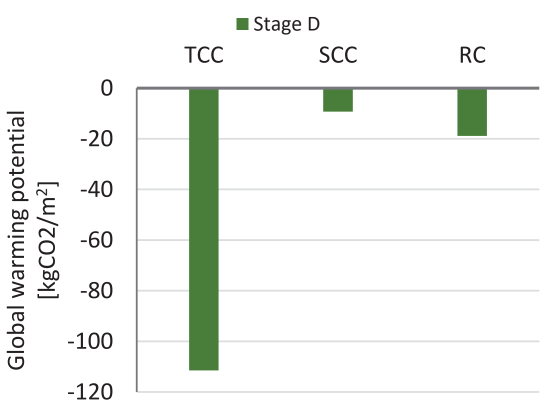


***Figure 6:*** *Comparison of the GWP from benefits and loads beyond the system boundary for TCC, SCC, and RC floor system*

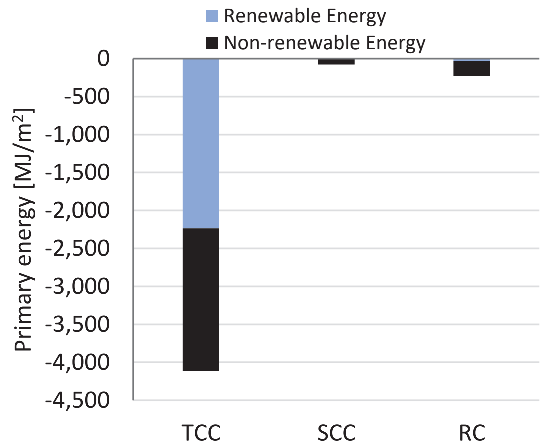


***Figure 7:*** *Comparison of the PE from benefits and loads beyond the system boundary for TCC, SCC, and RC floor system*

## 4 COMPARISON OF POSSIBLE END-OF-LIFE SCENARIOS FOR TCC

Knowing the TCC floor system has sustainable advantages compared to SCC and RC floors, different possible EoL cycle scenarios can be studied to compare their benefits toward finding a more sustainable solution. The assumed EoL cycle stages are shown in Figure 8. Since the production and use stages are identical, only stages C and D vary between the scenarios. For all the scenarios, the materials in the TCC slab are considered for de-construction (C1), transportation (C2), and waste processing (C3). The steel parts such as reinforcements and the bolts are recycled and the concrete is downcycled. Then, three different scenarios are studied for the CLT panel. The first scenario is identical to the one in the previous part which considers the benefits of timber for full energy recovery by incineration of wood to generate steam heat energy or electricity. On the other hand, a study [17] shows that in Europe on average 37% of wood products go to disposal while 33 % is recycled and the rest is used to produce energy. For disposal, the wood is interred in a landfill where the methane produced from its decomposition can also be harnessed to produce electricity. As for recycling, wood waste can be processed into engineered wood products and paper [18]. Therefore, the second scenario is considered the prevailing scenario in Europe with the combination of the mentioned proportions for disposal, recycling, and energy production. Then again, the environmental impact of a component can be reduced significantly when it is designed for deconstruction and reuse which is the aim of the ECON4SD building prototype 3. Therefore, the third scenario considers that the CLT panel of the composite slab is fully reused with the assumption that the shear connection allows for such operation.


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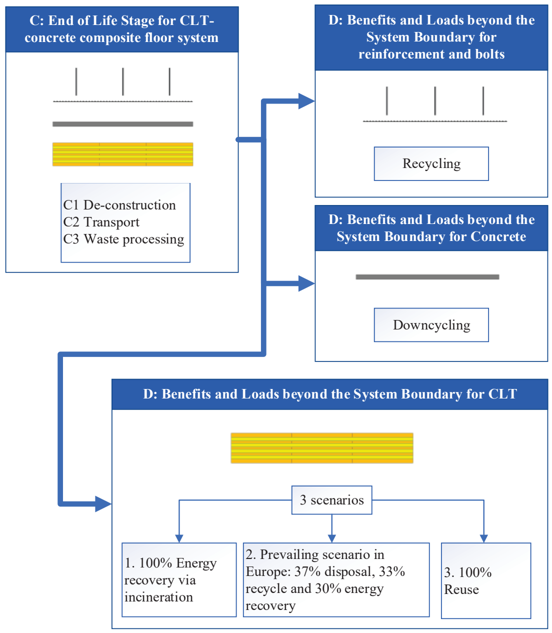


***Figure 8:*** *End-of-life scenarios of CLT-concrete composite floor system*

Although the different EoL scenarios do not affect the environmental impact in C1 and C2 stages, they influence the C3 stage. This impact can be seen in Figure 9 and Figure 10 with the CTG calculation of the GWP and PE. The second scenario has about two times more GWP than the other two scenarios. The third scenario has about 25% less GWP than the first scenario. Considering PE, the renewable required energy is almost the same for all scenarios. However, regarding the non-renewable PE, the third scenario is again the most sustainable solution demanding about 15% and 7% less PE compared to the first and second scenarios, respectively.

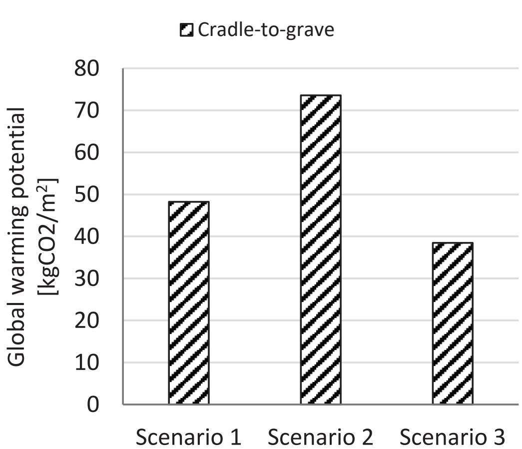


***Figure 9:*** *Cradle-to-grave GWP of the three different EoL scenarios for the TCC floor system*

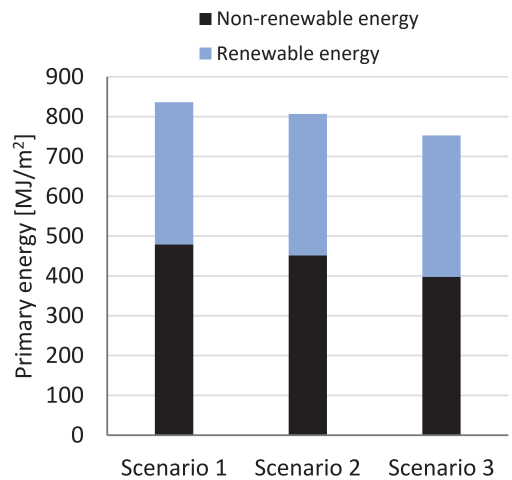


***Figure 10:*** *Cradle-to-grave PE of the three different EoL scenarios for the TCC floor system*

The benefits and loads of the three scenarios in stage D are compared in Figure 11 and Figure 12 as recovered GWP and PE, respectively. The first and second scenarios have almost the same GWP potential benefits while the GWP for the third scenario is more than 2 times higher compared to the other two scenarios. The maximum possible recovered primary energy is from the first scenario followed by the third and second scenarios. This is due to the recovered energy from the incineration of the timber in the first scenario. However, the third scenario has the most renewable energy. Therefore, among the three scenarios, the third scenario has the least environmental impact and the most benefits beyond the system boundary.

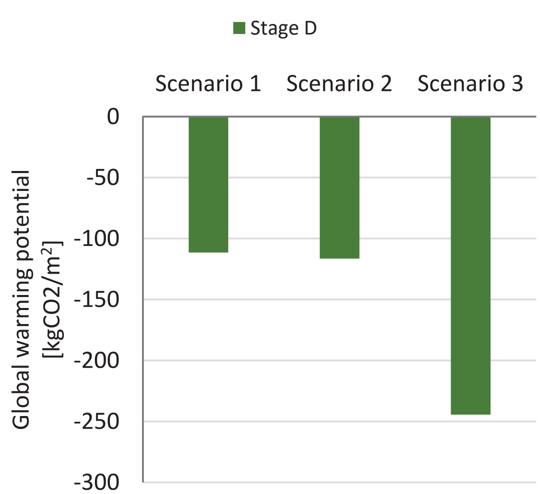


***Figure 11:*** *Stage D potential benefits for GWP of the three different EoL scenarios for the TCC floor system*

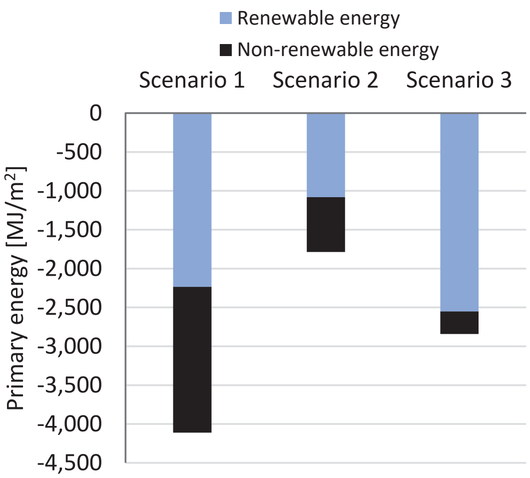


***Figure 12:*** *Stage D potential PE recovery of the three different EoL scenarios for the TCC floor system*

## 5 CONCLUSION

Three different floor systems are designed for the prototype building of the ECON4SD project considering the same loading condition and life span. The results show that:

- The global warming potential of the TCC floor system is one-third of the RC floor.
- The demanded primary energy of the TCC floor system is half of the RC floor.
- The TCC floor has significantly higher environmental benefits in stage D of the LCA compared to the other two floor systems.

Additionally, three different EoL cycle scenarios are compared for the CLT panel including full energy recovery, the prevailing scenario in Europe with a combination of energy recovery, disposal and recycling, and full reuse of the CLT. The comparison shows that reusing the CLT is the most sustainable solution since it has the lowest GWP and required PE. Also, the environmental benefits of the reuse scenario are more sustainable considering both GWP and PE measures. Therefore, for the studied building, a demountable and reusable TCC floor system is the most sustainable solution.

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