Life-Cycle of Structures and Infrastructure Systems – Biondini & Frangopol (Eds)

Impact of end-of-life stage in cradle-to-cradle LCA analysis of timber and timber-hybrid buildings

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ABSTRACT: Timber and hybrid timber buildings are very-well known for their properties of optimizing structural performances through a forward-looking combination of timber with other materials. These types of structures are also more sustainable from environmental perspective if compared to traditional RC buildings, especially considering the End-Of-Life stage (stage C) and Beyond System Boundary Stage (stage D) of Life Cycle Assessment (LCA) analysis where timber members contribute to the reduction of e.g., Global Warming Potential, given their very low – or even negative – values in terms of released kg CO_2 eq.

Two main issues have been identified by the authors concerning assessment of that topic, as first of all no standard methods are available for stage D impact evaluation; this problem is exacerbated by data shortage, given that this stage is currently not compulsory in the development of LCA analysis. In order to standardize this phase with the goal of spreading its importance, the authors investigated different case studies. Analysed previous studies are also needed for the second issue development, as a point of primary importance is the building structural scheme, with particular focus on fastening technology. Considering re-use, recovery or recycling potential of a building part or member, a key issue is the disassembling simplicity: this characteristic should be definitely taken into account in a cradle-to-cradle LCA analysis as this is the unique way to design the building in sustainable terms.

Reducing number of steps from building dismantling to the new building construction and minimizing amount of materials destined for disposal become measures of the building ability to reverse CO_2 emissions to zero or negative values with stages C and D detailed assessment.

1 INTRODUCTION

Nowadays global attention is focused on environmental impact of every product and process, with special careful on emissions of each phase of the life cycle, starting from the raw material extraction to the end-of-life, possibly including re-use, recovery or recycling procedures. This special care is needed as the current situation is the result of the last decades continuously increasing harmful emissions which are leading to irreversible damaging of the planet (Solomon, Plattner, & Knutti, 2009). The issue is complex as several problems can be identified, apart from already mentioned matter of emissions quantities; resources exploitation by the most developed countries is no more compatible with the Earth's capacity to regenerate these resources. This unbalance reflects in every aspect of human life, from the economical, to the social and health aspects (Lenton, et al., 2019) (Markkanen & Anger-Kraavi, 2019). In Figure 1 two indicators of the gravity of the situation are represented.

Climate change has been treated for years as a slow process which implications would have been far away in time: this assumption is proven to be wrong, just considering sudden temperature growth. This laxity has placed both changes observations and mitigation measures in a secondary position that lead to even more severe consequences that nowadays are visible to everyone. Another issue that draws the attention on the topic is the irreversibility of some processes, such surface's temperature increase that continues growing even though CO_2 emissions are reduced to zero, following a hysteretic path behaviour delayed in time (Soong-Ki, et al., 2022).

DOI: 10.1201/9781003323020-364

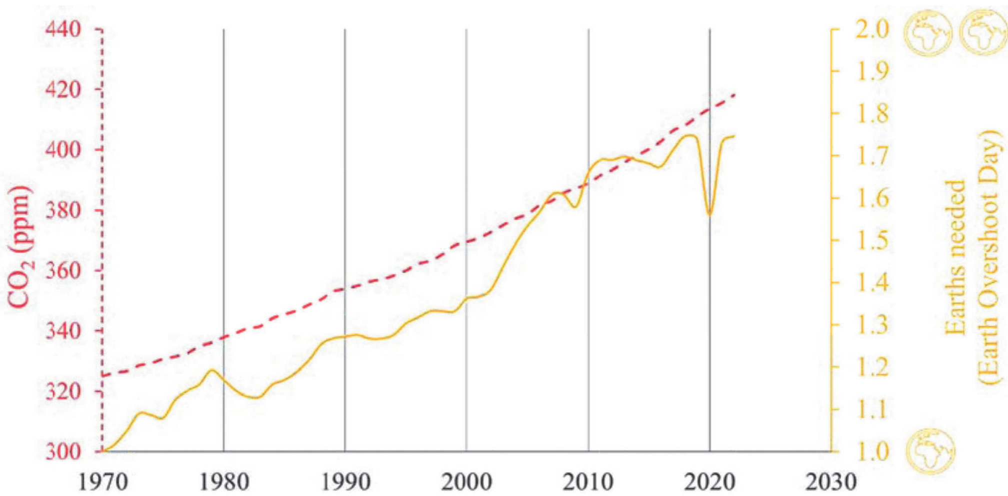

Figure 1. Carbon dioxide concentration in part per million (https://gml.noaa.gov/webdata/ccgg/trends/co2/co2_mm_mlo.txt) and Earth Overshoot Day starting from 1970 (https://www.overshootday.org/newsroom/past-earth-overshoot-days/). Year 2020 drop of the Earth Overshoot Day is caused by pandemic lockdown effects.

Considering that building and construction sector is responsible for almost 40% of the emissions (Jahan, et al., 2022) (taking into account both energy usage and processes related) and that the building stock is growing in order to accommodate increasing population especially in urban areas, a special effort is required. Considering annual reports delivered by the Global Alliance for Buildings and Construction (GABC) that started monitoring the sector under consideration from the COP21, some mild improvements have been noticed, as the increase of green building certifications (Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector, 2021) Considering on the other hand the building sector emissions, last two years data – in particular year 2020 – have recorded significant decrease, which is again a pandemic effect that hides the fact that building decarbonization is not on track.

This fact claims for new solutions and greater attention in terms of sustainability actions for new and existing buildings. Considering new buildings, the sustainability perspective is imperative and of primary importance; on the other hand, also existing buildings should be considered. These buildings will contribute to waste generation once reached their end-of-life, which treatment contribute to soil consumption, power usage and greenhouse gases emissions (Alsheyab, 2022), even though applying a waste management hierarchy significant mitigation of impacts is granted (Sasitharan, et al., 2012). Amount of waste generated by construction and demolition (C&D) contributes worldwide for about 25% of the total generated waste, even though discrepancies are recorded for different countries (Nunes & Mahler, 2020), which again establishes an alarming datum. Reuse, recycling and recovery must be always hierarchically considered to guarantee a sustainable management, as sketched in Figure 2.

Figure 2. Waste management sustainability, adapted from Sasitharan, et al., 2012.

In a holistic approach to guarantee sustainability, it turns crucial to monitor each phase of the building's life by Life Cycle Assessment (LCA) analysis. This is a worldwide-accepted method whose main outcomes are classified with a tree-model of impacts. Considering e.g., carbon dioxide (CO_2) emissions, the resulting effect is interpreted in terms of climate change which is part of the macro category of harmful effects on the ecosystem. In this way a methodological approach is available for evaluation and comparison of different technologies, even though some shortages are noticed; the main issues are linked with phases C (End-of-Life stage) and D (Benefits and Loads beyond the System Boundary) of LCA. First of all these stages are intrinsically affected by indelible uncertainties due to their non-immediate applications, as they are expected to be involved some decades later than building design phase. Moreover, given that stage D is nowadays not mandatory, low level of standardization and short amounts of data are available in literature (Delem & Wastiels, 2019).

Considering a sustainable building, an interesting solution lies in Timber-Concrete Composite (TCC) buildings, which optimize timber in an engineered perspective and reduce concrete volumes. In more general terms, engineered timber products like CLT, Glulam, LVL... are characterized by low values of carbon footprint thanks to a low-energy consumption production process (Khorsandnia, Valipour, Schänzlin, & Crews, 2016), reduced construction times compared to traditional RC buildings (Mirdad, Daneshvar, Joyce, & Chui, 2021), lower values of density-to-strength ratio and reduced thermal conductivity (Khorsandnia, Valipour, & Bradford, 2018); moreover the concept of disassembling simplicity is more readily enforceable with members made by timber-based products (Bertino, et al., 2021). In this way e.g., deconstructable connections facilitate dismantling and recycling processes, leading to lower waste amounts (Derikvand & Fink, 2021), which imply less material destined to landfilling, a reduction of dismantling times and preservation of natural resources (Hradil, et al., 2014). Almost all of the current studies on connectors accurately focus on their performances (Mirdad, Khan, & Chui, 2022), without explicitly considering the fact that they may hinder building deconstruction and saving of the greatest possible quantity of materials, so without carrying out environmental considerations.

The authors suggest an overview of today's practices concerning the End-Of-Life management of TCC buildings, with a focus on fastenings technology and their disassembling simplicity, range of expected scenarios (Quéheille, Ventura, & Saiyouri, 2022), convergence towards a cradle-to-cradle approach and waste minimization through reuse, recycling and recovery. Nowadays most widespread approaches are cradle-to-grave (from stage A to stage C of LCA) and no or limited alternative scenarios are generally considered (Allan & Phillips, 2021). Moreover, given the actual difficulty in finding literature where the issue of scenarios concerning End-Of-Life stage is assessed considering also disassembling simplicity, an innovative perspective towards a closed loop in terms of LCA is suggested.

The paper is organized as follows. Section 2 presents the method applied for literature selection 2. Results of such phase are presented in Section 3, identifying main strategies for stages C and D of LCA and detecting common disassembling procedures. Finally, Section 4 provides discussion of results and conclusions.

2 METHOD

The methodology adopted for this study consists of different steps sorted in this way:

i. Identification of literature concerning End-Of-Life and Benefits and Loads beyond the System Boundary stages with focus on timber or timber-hybrid buildings. The reason of the emphasis on buildings with timber members lies in the fact that accurate scheduling of dismantling phase should be foreseen; otherwise, environmental advantages of using timber-based products is – at least partially – missed. This first step pursues the aim of creating a photograph of current considerations of such phases.
ii. Analysis of widespread scenarios for End-Of-Life stage. The aim of this step is highlighting importance of accurate considerations taking into account uncertainties that naturally occur due to long terms and deficiency of real-cases data.
iii. Detection of fastenings common technologies and analysis of disassembling procedures with identification of common patterns. Disassembling simplicity always guarantees the

most efficient solution in terms of sustainability; by observing Figure 2, it is clear that apart from comparisons of the solutions at the opposite ends, also consecutive approaches bring different levels of emissions. Comparing e.g., reuse and recycling, the second solution includes some manufacturing processes that generate Greenhouse Gases (GHG), while the first one does not need any working process.

iv. Proposal of a flow chart in order to facilitate the transition from the current most widespread cradle-to-grave approach to the more forward-looking and sustainable cradle-to-cradle one, where the concepts defined in points ii. and iii. are assessed together.

The suggested method starts from a literature review in order to offer an innovative methodological approach, especially designed for timber-hybrid buildings.

3 RESULTS

Literature retrieved during the review is formerly subdivided in three categories, according to the topics addressed in the work. Considering the issues of End-of-Life scenarios and of disassembling simplicity, the following classes of papers are identified:

a. Articles with focus on strategies for LCA's stages C and D and without consideration of connectors role in disassembling procedures. The following papers are identified: Quéheille, Ventura, & Saiyouri, 2022, Tam & Tam, 2006, Mirdad, Khan, & Chui, 2022, Jahan, Zhang, Bhuiyan, & Navaratnam, 2022, Nunes & Mahler, 2020, Younis & Dodoo, 2022, Lukić, Premrov, Passer, & Žegarac Leskovar, 2021, Bertino, et al., 2021, Hart & Pomponi, 2020, Niu, Rasi, Hughes, Halme, & Fink, 2021, Alsheyab, 2022, Condotta & Zatta, 2021, Hradil, et al., 2014, John & Buchanan, 2013. The most widespread scenarios are: 1) reuse of timber-based materials panels; 2) recycling of timber-based panels with production of microchips and production of new panels without usage of virgin resoruces; 3) energy recovery through incineration and reduction of natural gas use; 4) landfilling, which is substantially a non-development of stage D.
b. Articles addressing the connectors role in disassembling procedures and not focusing on strategies for LCA's stages C and D. The following papers are identified: Derikvand & Fink, 2021, Khorsandnia, Valipour, & Bradford, 2018, Derikvand & Fink, 2020, Khorsandnia, Valipour, Schänzlin, & Crews, 2016. These studies present experimental and numerical results of different TCC connections, with comparisons between permanent and deconstructable solutions. In general terms, even though some quantitative predictable differences, failure modes are comparable according to some expedients as insertion of internal threads in the PVC plug (Derikvand & Fink, 2020) or different angles of connectors insertion and different timber joists thickness (Khorsandnia, Valipour, Schänzlin, & Crews, 2016).
c. Articles dealing both with the connectors role in disassembling procedures and with strategies for LCA's stages C and D. The following papers are identified: Hafner, Ott, Bodemer, & Winter, 2014, Cristescu, et al., 2020, O'Grady, Minunno, Chong, & Morrison, 2021.

In class a. 14 papers are collected, while just 4 articles are included in b. class; on the other hand, 3 articles consider both topics of classes a. and b., populating class c. Considering aforementioned literature, Table 1 lists recurrent topics for classes a. and b., thus common best practices and widespread investigated issues are detected.

Considering subjects listed in Table 1, they clearly reflect the current approach that still struggles to reach a circular economy outline, as detected best-researched topics are strongly related to a two-track view; thereby a flow chart with an innovative methodological approach is suggested in. The role of this original perspective arises from the necessity to take into account together structural and environmental requirements, as nowadays – as confirmed by literature review outcomes – the trend is closer to a separated approach, with some serious practical and methodological shortcomings. The proposed tool is a methodological and theoretical support which recommends some best practices which mainly lead to structural and environmental advantages: disassembling simplicity significantly reduces dismantling times, with dropping of GWP gases emissions and greater reuse rates of e.g., timber-based products panels.

Table 1. Recurrent topics for two literature categories identified.

Strategies for LCA's stages C and D	Connectors role in disassembling procedures
• Development of different scenarios • Waste management: assessment accuracy as a function of the country's sensitivity to environmental issues • Overview of recycling technologies • Importance of comparative LCA • Rising importance of circular economy • Critical considerations of unavoidable uncertainties linked with broad temporal perspective	• Comparative failure analysis of permanent and deconstructable shear connectors • Investigation of different alternatives with comparisons of waste at the End-of-Life stage of the building • Disassembling simplicity before and after load application • Identification of obstacles in disassembling procedures that hinder timber re-use

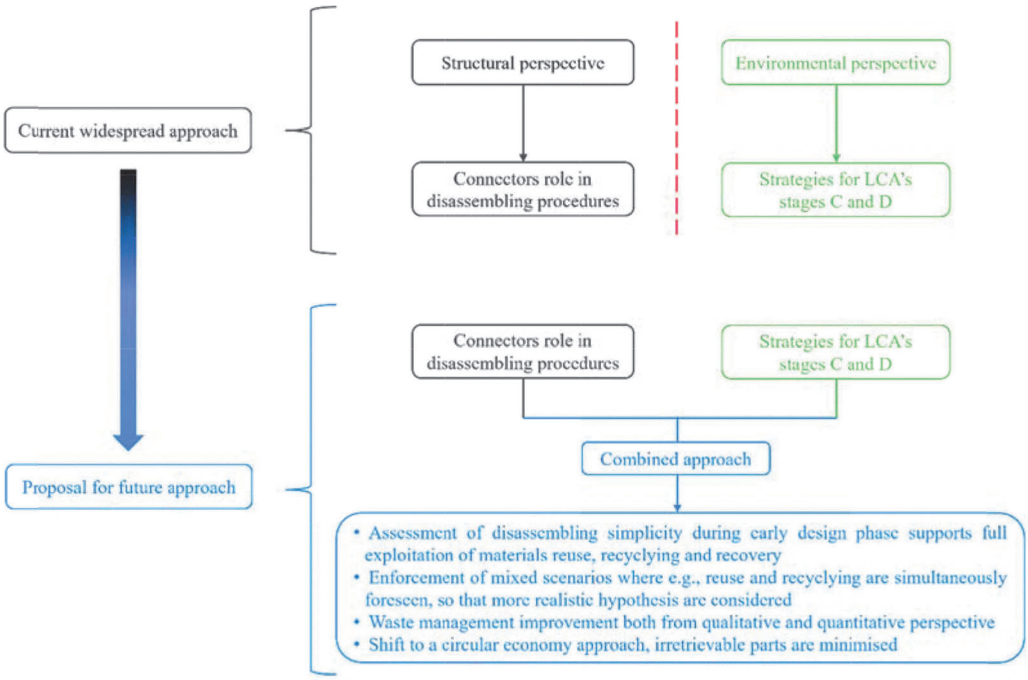

Figure 3. Flow chart with authors' original proposal concerning the combination of structural and environmental requirements.

One of the issues nowadays scarcely considered is the possibility to foresee different scenarios, as e.g., considering just a reuse hypothesis may be limiting, even if this is the most preferable from a sustainability perspective.

Unexpected events and damages experienced and encountered during the dismantling phase may hinder a "total reuse" scenario, so it is worth providing one or more alternative chances where damaged parts are not directly destined for landfilling, but recycling is scheduled, chips are produced, and virgin material is not used for panels manufacturing. This example represents how a combination of both structural and environmental points of view is extremely favourable, even though up-cycling is not always totally practicable. Moreover, this approach reduces wastes both from physical (materials) and organisational (times and costs) sides. An example of applicability of a mixed scenario is presented in Figure 4, where firstly reuse of suitable parts is carried out and recycling of portions probably damaged during dismantling is suggested.

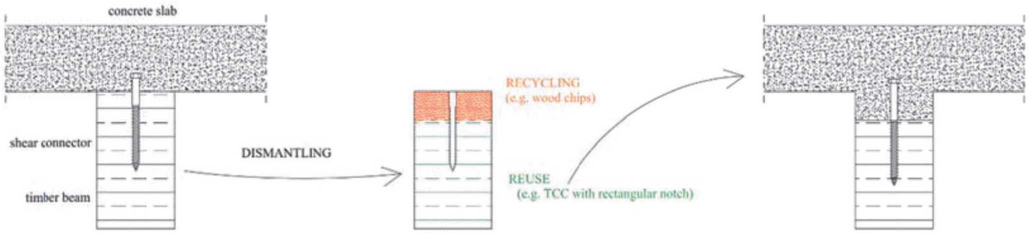

Figure 4. Example of reuse and recycle of a timber beam from a TCC slab.

4 DISCUSSION AND CONCLUSIONS

The literature review acknowledged that environmental and structural fields still suffer of a communication problem; the fact that environmental issues linked to the building sector have been realised in recent years, while the structural side is obviously the core of this field, produced some gaps that still need to be filled.

This work first proposes as a preliminary methodological research which findings are mainly:

i. Identification of research shortcomings, mainly detected in the missing relationship between structural and environmental requirements.
ii. Dismantling procedures are generally not accounted for during building design phase, so at the End-of-Life many uncertainties that increase times and costs should be faced.
iii. Planning of building End-of-Life is becoming widespread from a theoretical point of view, such that a plurality of scenarios is always more frequently suggested.

In addition to such methodological observations, the paper proposes an innovative outlook concerning simultaneous consideration of structural and environmental requirements. First of all, the novelty introduced by the flow chart presented in is the concomitant mention to connectors and their role in building dismantling, stages C and D of LCA, sustainable waste management and consequently reasonings towards a circular economy approach. An example of such approach is reported in Figure 4, where a TCC solution is conceived according to a reuse and recycle scenario.

Finally, the proposed approach paves the way to future developments, where considering buildings impact on climate change is everyday more urgent; it is expected that building environmental standards will become more stringent, so a close link between structural and environmental requirements is no longer deferrable; this cooperation is intended as an optimization on both sides, with an accurate design of connectors in order to guarantee the maximum rate of material to be reused in a cradle-to-cradle approach.

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