IOP Conference Series: Earth and Environmental Science

PURPOSE-LED PUBLISHING™

PAPER • OPEN ACCESS

Innovative robotic-woven willow-clay-composite ceiling elements

To cite this article: Simon Steffl *et al* 2024 *IOP Conf. Ser.: Earth Environ. Sci.* **1402** 012034

View the article online for updates and enhancements.

You may also like

- Estimating integrated measures of forage quality for herbivores by fusing optical and structural remote sensing data
  J S Jennewein, J U H Eitel, K Joly et al.
- Reindeer grazing increases summer albedo by reducing shrub abundance in Arctic tundra
  Mariska te Beest, Judith Sitters, Cécile B Ménard et al.
- Resource potential and properties of cellulose obtained from tree willow wood
  A A Paramonov, J V Sevastyanova, S V Tretyakov et al.

This content was downloaded from IP address 141.52.248.4 on 15/10/2024 at 13:31

IOP Conf. Series: Earth and Environmental Science **1402** (2024) 012034 doi:10.1088/1755-1315/1402/1/012034

Innovative robotic-woven willow-clay-composite ceiling elements

Authors: Simon Steffl[1] *, Rebekka Volk[1], Moritz Dörstelmann[2], Frank Schultmann[1]

[1] Karlsruhe Institute of Technology (KIT), Institute for Industrial Production (IIP), Hertzstr. 16, 76187, Karlsruhe, Germany

[2] Karlsruhe Institute of Technology (KIT), Institute for Digital Design and Fabrication (DDF), Englerstr. 7, 76131, Karlsruhe, Germany

*Corresponding author: simon.steffl@kit.edu

Abstract. The construction sector contributes 36% to global final energy use and 39% to energy-related CO2 emissions. Consequently, it is imperative to focus on quantifying and reducing environmental impacts e.g., via renewable building materials. The combination of fast-growing willow as tension reinforcement for regionally available and compression bearing clay seems a promising approach. The new attempt is based on the idea of full circularity, as the willow clay composite modules are in the first loop dismountable and can be rearranged and reused for another life cycle. When the composite material comes to its end-of-life, the materials can be theoretically fully recovered. To assess the environmental sustainability of such an innovative composite structure for the first time, a simplified cradle to grave Life Cycle Assessment is performed. The investigation is based on experimental data of the 1 to 1 scale robotically woven willow-clay-composite ceiling demonstrator. First results reveal hot spots, especially in the supply chain of the prototype production process but compared to conventional steel concrete ceiling, the innovative biobased composite is capable to function as a CO2 sink over the entire life cycle. In addition, the resource problem of timber could be circumvented accordingly.

Keywords: construction industry, industrial ecology, biomaterials, circular economy, environmental assessment, life cycle assessment

1. Introduction

For the earliest buildings, native soil plant fibers, timber, and straw were used together with local earth and clay in vernacular construction processes which were characterized by low emissions, selective and diversified use of local materials and a high demand for skilled crafts. But over the years, these traditional building materials became less relevant because of growing performance requirements in construction as well as changes in design and manufacturing practice favoring ease of fabrication over material efficiency in a development agnostic to its environment impact. Steel and concrete can meet the material requirements of the new dimensions within the modern built environment. [1, 2]

However, today's construction practice makes a huge contribution to climate change. Renewable biogenic materials have drawn recently more attention due to their ability for substituting high-energy and high-emission construction materials [3–5] . Since massive CO_2 reductions in the construction sector are necessary to meet the climate targets [4], research and development in this field is expanding. Particularly, construction components manufactured from rapidly growing plant-based components like willow or bamboo might be promising materials because of their capacity to build up biogenic carbon

Content from this work may be used under the terms of the Creative Commons Attribution 4.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd

stock sequestered from atmosphere as well as their fast regeneration/regrowth periods [6]. Additionally, compared to conventional building materials, their production frequently uses less energy. Since most production sites are using energy mixes with a high fossil share a low-energy production reduces the use of fossil fuels and helps to prevent CO_2 emissions [3].

Environmental assessment for wood and timber as building materials are readily accessible in literature [7–11]. When end-of-life credits are taken into account, timber and wood-based architecture has a CO_2 advantage over buildings with concrete [12]. However, the supply of wood and timber with regard to sustainable time horizons for regrowth is a major disadvantage and contradicts sustainability principles [13]. Since renewable raw materials are often not locally available, they nowadays have to be transported over larger distances. Large transportation distances and the possibility of acidification are potential drawbacks for renewable raw materials, similar to plant fibers [14].

So far, willow was grown on so-called short rotation coppice for biomass production and basket weaving rather than being employed for construction purposes [15]. There are no Life Cycle Assessment (LCA) data or studies available for the natural production of willow for usage in construction [16, 17]. Fertilizers are important for a fast building up of willow biomass [16]. However, this has the potential to generate high levels of eutrophication and acidification as well as scarcity of fossil fuels. Although fertilization of willow plantations is not required for the provision of nutrients, it is nonetheless commonly applied due to its ability to increase the biomass output. [14, 18, 19]

The second main component of the sustainable construction composite system is a low-processed clay mix, that is capable to reduce embodied emissions and energy of a building [20, 21]. Evaluation of clay-based construction materials from cradle to grave discovered that transportation is a hot spot when it comes to ecological sustainability [22, 23]. Thus, in construction the local sourcing of both willow and clay are crucial when aiming for an environmentally friendly construction. Furthermore, the possibility of recycling at the end of a product's life generates benefits since primary resource extraction is prevented [24, 25].

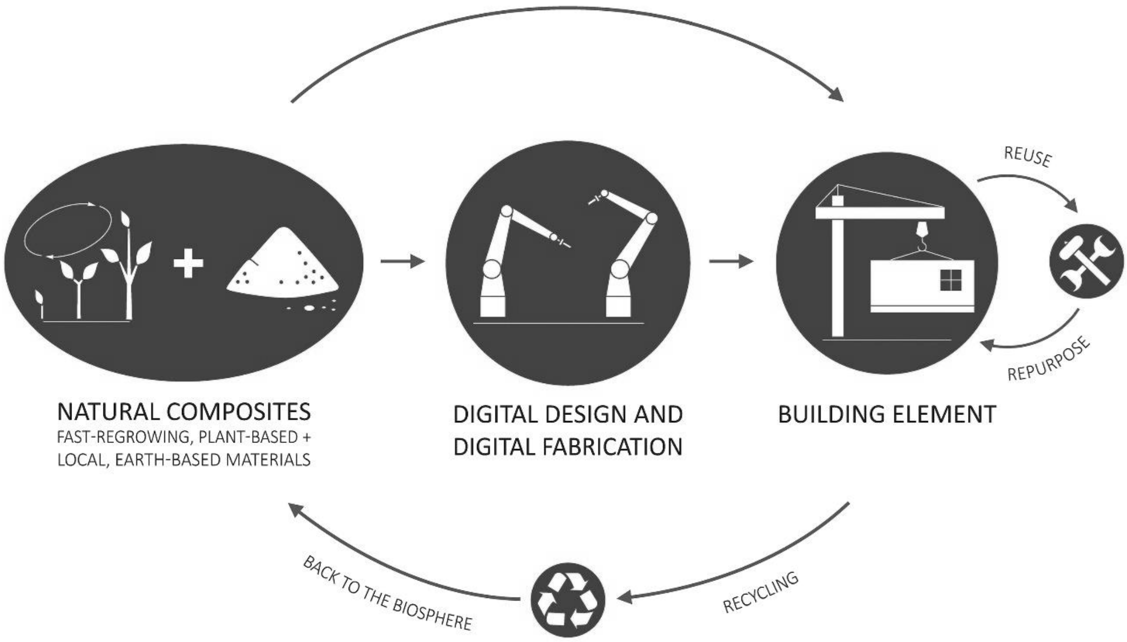

Figure 1. Circularity concept of willow clay composite construction material (©ddf/KIT)

In figure 1 the circularity concept of the willow clay composite in construction application is shown and indicating full circularity of the main components. Although it has been shown that clay construction

IOP Conf. Series: Earth and Environmental Science **1402** (2024) 012034 doi:10.1088/1755-1315/1402/1/012034

products can potentially be recycled, the majority of life cycle assessments in literature only take backfilling and landfilling into account as recycling options [21, 23]. Despite these existing approaches, there are still research gaps that need to be addressed, which this contribution aims to achieve. The CO2e balance over the entire life cycle of the willow-clay-composite element is assessed and compared with a traditional steel concrete ceiling element.

Main research question is:
What is the environmental effect of a ceiling element made of willow and clay composites and how does it compare to a traditional steel reinforced concrete ceiling element?
For this, we investigated and assessed the whole life cycle and expanded on previous life cycle assessments (LCA) research to find the most important life cycle stages, raw materials, and procedures in the evaluation of a willow-clay composite ceiling (section 2). Furthermore, the potential for optimizing the ceiling system's environmental quality is being explored. And finally, results are discussed and an outlook is given (section 3).

2. Life Cycle Assessment (LCA)

In addition to creating experimental data for the new building and production method, this study performed a simplified attributional life cycle assessment and a comparison with a standard reinforced steel concrete ceiling (RSCC). The modeling and assessment were carried out in SimaPro Version 9.4.0.2 in compliance with DIN EN 15804+A2. Along with the datasets Ecoinvent v3.8 („Allocation, cut-off by classification - Unit “) and Agribalyse v3.1 („Agribalyse - Unit”) the cut-off method was used which goes along with the polluter pays principle according to the system boundary definition in standard DIN EN 15804.

2.1 Goal and Scope

In this study, the Willow-Clay-Composite Ceiling (WCCC) was assessed from cradle to grave (modules A, C, and D), excluding the usage phase. This encompasses the cultivation of willow derived from short rotation coppice, preprocessing for enhanced rod flexibility, innovative robotic processing and weaving, clay filling into molds, component drying in ambient air, and transportation (A), as well as the complete downstream process, from deconstruction to traditional end-of-life (EoL) scenario (C). The system boundaries for the considered sources, production, and end-of-life scenarios incorporate loads and benefits from clay- and metal recycling, along with energy utilization of the biomass (D). The use phase was not assessed since many unknown parameters would have to be simulated. And, for comparison purposes the excluded use phase for both alternatives do not change the relative comparison results.

This investigation's functional unit is the construction of a one-square-meter ceiling element constructed of clay and willow, including the procurement of materials and end-of-life processing. Throughout its expected 50-year lifespan, this element is assumed to withstand a maximum load of 10 kN/m^2 and weights a total of 398 kg. Its thickness ranges from 200 to 430 mm. All of the design's functional components are taken for granted.

The measurements fit the profile of a 1200 mm-span single-span beam. The willow-clay ceiling elements have been structurally tested to a maximum breaking load of 34 kN/m^2. Considering an accumulative safety factor on material properties and load cases, the WCCC can be assigned to the load category of C4 and C3 (5kN/m^2) including smaller load categories C2 (4 kN/m^2) and C1 (3 kN/m^2). This is comparable to a busy place with tables, like a restaurant or a busy classroom. With this payload, offices (category B) and homes (category A) are also conceivable. [26]

The EoL scenario examines the impact of underlying data, assumptions, and uncertainty for assessing the environmental impact derived from recycling steel and clay, as well as from incineration of the willow.

2.2 Impact assessment

A comprehensive environmental evaluation is conducted from cradle to grave with a potential end-of-life outcome. The impact of primary material production is offset by rewarding products and sellable by-products, following the avoided burden approach [27]. The impacts are distributed based on weight, and intermediate products carry the burdens of the preceding stages.

To align with other Environmental Product Declarations (EPD), the Life Cycle Assessment (LCA) evaluates the impact categories climate change impact (GWP) and cumulative energy demand (CED) shown in Table 1.

Table 1: Investigated impact categories

Impact category	Abbreviation	Unit	Method
Global Warming Potential (GWP 100a) • *Fossil* • *Biogenic +* *Land use and land use change*	GWP *GWP-F* *GWP-B +* *Luluc*	kg CO_2-eq.	EN 15804 + A2
Cumulative Energy Demand • Non-renewable • Renewable	CED CED-NR CED-R	MJ	Cumulative Energy Demand (LHV)

2.3 Life cycle inventory

Both the production and end-of-life phases have defined mass and energy balances which form the basis of the LCA. A significant amount of the Life Cycle Inventory (LCI) data was experimentally gathered during the prototype manufacturing process and in cooperation with raw material suppliers, farmers, and producers in order to meet the highest standards of data quality and precision in the assessment model. Literature and databases were used to fill up any data gaps.

To fully evaluate the raw material sourcing process, the farmer's empirical data was used to project and assess the production of willow rods for construction purposes, together with information from Ecoinvent and Agribalyse databases. In addition to supplier data, further supplies customized for the case study are obtained from Ecoinvent and Agribalyse databases, including metals, clay, wood, reed, and sisal yarn which was taken as a data substitute for yute yarn.

Scales and an electricity meter were used to monitor data on material and electricity usage during manufacturing in order to assess the novel freeform weaving technique. Regarding the construction and deconstruction on-site, assumptions on an installation via crane based on experience were made. The WCCC end-of-life evaluation (phases C+D) is based on assumptions rather than experimental data, in contrast to the upstream value chain of WCCC manufacturing, because the prototype's actual destruction, recycling, and disposal have not yet taken place.

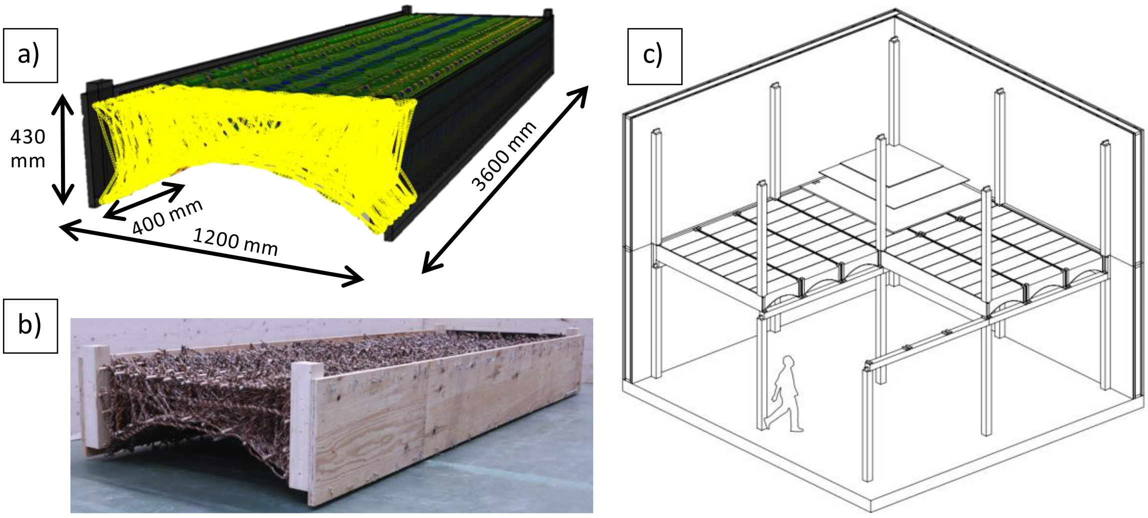

Figure 2. a) digital model of the unfilled and assembled WCCC-element (©ddf/KIT), b) prototype unfilled and assembled WCCC-element (©ddf/KIT), c) installation sketch on a multi-story pavilion with WCCC ceiling elements (©design and building construction/KIT)

To assess the environmental impact that is associated with the willow production, assumptions based on interview with a willow farmer were made. Until now, willow cultivation for biomass production is done in short rotation coppice with a service life of 20 to 30 years and at least three years rotation cycle between harvests [15], [28]. In contrast, the assessed willow agriculture for construction materials has a service life of 27.5 years and annual harvesting. The annual harvest is 7500 kg absolute dry mass per acre, of which 90% are saleable willow branches and 10% are rejects that can be used for further cultivation. The cultivation which was assessed is done without fertilizers, pesticides and artificial irrigation [19].

To account for environmental effects of the upstream and downstream processes within the system boundaries, the SimaPro and Agribalyse data was adjusted by the electricity consumption during willow production in connection with diesel consumption during willow cultivation, all transports, on site erection via crane (construction) and deconstruction [29].

In the following, the life cycle stages and corresponding processes within the LCA are described. More information regarding the data origin can be found in Table 2.

- Phase A1-A2: material sourcing & supply (WCCC)
    - Willow supply chain (plowing of the old plantation, weed control, new plantation set up, control drive, maintenance measures, harvest and transport to production facility)
    - Yute yarn supply chain incl. transport to production facility
    - Adhesive supply chain incl. transport to production facility
    - Laminated veneer lumber supply chain incl. transport to production facility
    - Wooden round bars and squared timber supply chain incl. transport to production facility
    - Clay mix (clay production, sand, crushed gravel, reed, straw) supply chain incl. transport to production facility
    - Steel products supply chain incl. transport to production facility
- Phase A1-A2: material sourcing & supply (RSCC)

  - Steel products supply chain incl. transport to production facility
  - Concrete supply chain incl. transport to production facility
- Phase A3: production (WCCC)
  - Milling of the veneer lumber board
  - Preprocessing of the willows for flexibility
  - Extrusion, bunching and robotically weaving process of the endless spliced willow rods via robot
  - Mixing the clay with water, sand, crushed gravel, reed, straw
  - Assembly of nine weaving elements with veneer lumber board to a complete ceiling element (Figure 2 a, b)
  - Filling the clay mix in the willow weave ceiling element
  - Air drying of the finished WCCC element
- Phase A3: production (RSCC)
  - Production of steel mats using welding machine
  - Mixing the concrete with water and pouring with the reinforcing steel mats using large scale conventional concrete mixer (incl. all upstream processes Phase A1, A2)
- Phase A4-A5(WCCC): Transportation via truck of the prefabricated willow weave composite ceiling element from the production facility to the demonstrator exhibition site (75km), crane assisted erection on site
- Phase A4-A5 (RSCC): Transportation via truck of the prefabricated reinforced steel concrete ceiling element from the production facility to the demonstrator exhibition site (75km), crane assisted erection on site.
- Phase C1-C4: For RSCC deconstruction with hydraulic excavator and steel and concrete separation, followed by transport to waste processing facility (50km). For WCCC crane assisted deconstruction on site and transport to recycling facility (50km) are assumed. Material separation of organic fraction (willow, wood-based products) from minerals clay and steel products, post processing of separated material fractions, incineration of the organic fraction and final disposal of residues and complete recycling of the inorganic components clay, and for metal and concrete via conventional recycling routes recycling
- Phase D (WCCC): Incineration of organic material in a combined heat and power municipal solid waste incineration plant (33.5% thermal efficiency and 11.1% electric efficiency) [30] substitutes the generic heat and power supply of the German electricity and heat production mix based on the lower heating value of the accumulated organic material. The recycling of the clay fraction generates benefits for provisioning secondary clay mix and thereof avoided primary clay production. Same with the metal fractions, that substitute primary material sourcing.
- Phase D (RSCC): Recycling of concrete and steel substitutes raw material sourcing and receives credits for avoided primary material substitution of concrete (52% crushed gravel and 48% sand) and pic iron.

Table 2. Overview data ceiling elements

Material	Life Cycle Phase			Source
	Supply chain and production origin	End-of-Life	Benefits and loads	
WCCC	A	C	D	
Willow	Germany	Incineration	Energy utilization	adjusted SimaPro and Agribalyse
Yute yarn	Bangladesh	Incineration	Energy utilization	SimaPro
Adhesive	Global	Incineration	Energy utilization	SimaPro
Laminated veneer lumber	Swiss	Incineration	Energy utilization	SimaPro
Wooden round bars	Germany	Incineration	Energy utilization	SimaPro
Squared timber	Germany	Incineration	Energy utilization	SimaPro
Clay mix (clay, sand, crushed gravel, reed, straw	Germany	Recycling (incineration biomass)	Primary material substitution (minerals) and energy utilization (biomass)	SimaPro
Steel products	Europe	Recycling	Primary material substitution	SimaPro
RSCC	A	C	D	
Reinforcing steel	Europe	Recycling	Primary material substitution	SimaPro
Concrete	Austria	Recycling	Primary material substitution	SimaPro

2.4 Results

As shown in Figure 3, the GWP and CED of the assessed RSCC and WCCC are very different except for deconstruction, construction - installation. GWP and CED of both ceiling elements in the phases of construction and deconstruction are almost equal. Most significant is the absence of biomass in RSCC in contrast to the WCCC (green and blue bars). Therefore, no GWP-B+Luluc (green) and almost no CED-R (blue) account for the RSCC which significantly improves the benefits and loads, waste processing + disposal and the material sourcing of WCCC. But, is it also visible that the biomass usage advantages the material sourcing while it disadvantages the waste processing in almost the same height. GWP and CED of transport differ due to the different distances particularly for clay.

For the GWP-F of RSCC it can be stated that it is seven times greater than for WCCC because of the high greenhouse gas emissions caused by clinker production (material sourcing). When it comes to incineration of the WCCC's the biomass the GWP - B is pushed by the release of all the sequestered carbon that was bound in the biogenic material (waste processing + disposal). In the assessment, energy utilization was accredited within an electricity and heat mix substitution; thus GWP-B+LULUC deducts the value for GWP. Accounting for primary material substitution within clay and concrete recycling (benefits and loads) leads to a considerable deduction in GWP-F for both the RSCC and the WCCC. Finally, the total GWP over the entire life cycle of WCCC is about 40% of the GWP from a comparative RSCC element.

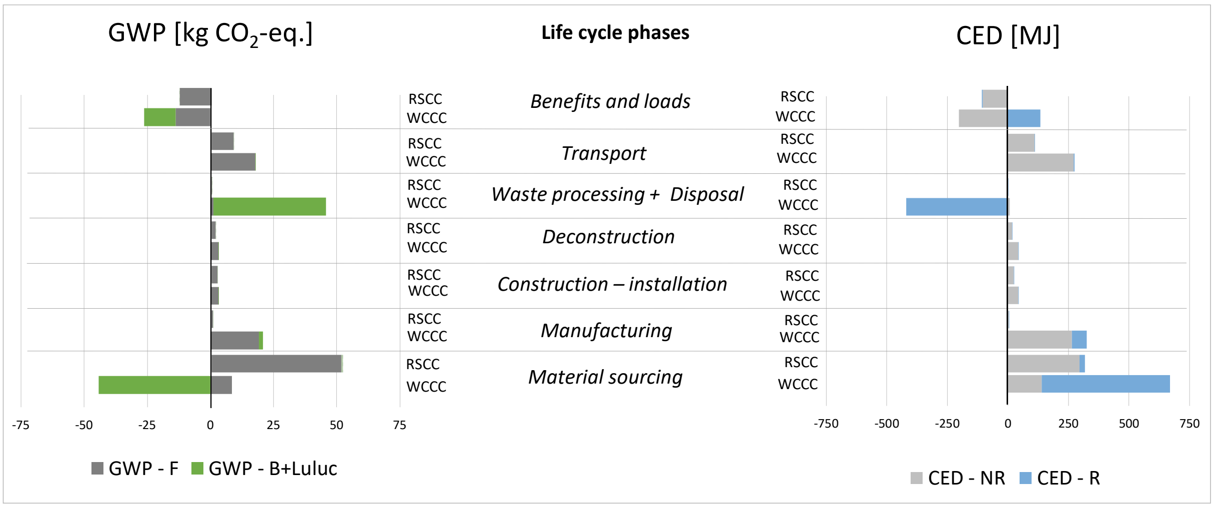

Figure 3. Absolute values of GWP-F, GWP-B+LULUC and CED-R, CED-NR of the comparative simplified LCA (cradle to grave) for WCCC and RSCC elements according to (EN 15804+A2, CED LHV 1.00)

In terms of CED, biogenic carbon within the CED-R plays a significant role for WCCC's material sourcing. RSCC does not include any renewable materials and therefor no CED-R can be accounted for it in this life cycle phase. The CED-NR of RSCC manufacturing is significantly lower than that of WCCC, most likely because of a very efficient mass production. Due to complete recycling of the two RSCC materials concrete and steel there are very few end-of-life effects that can be attributed to the RSCC (waste processing and disposal). For WCCC, the waste processing within the renewable material circle deducts the CED-R value since the biomass is incinerated and thus provides renewable energy (waste processing+ disposal). Caused by the comparatively long transport distances CED-NR of WCCC is much higher than of the RSCC. Within CED-NR impact category benefits from avoided primary material sourcing and supply of WCCC are almost double the value of RSCC. As concrete recycling leads to assumed low material substitution credits for the substitution of sand and crushed gravel, the recycling benefits are lower compared to the avoided primary clay mix by using recycling clay for WCCC (benefits and loads). In total, the CED (CED-NR+CED-R) of the WCCC over the entire life time exceeds the total CED of RSCC. When deducting for WCCC the CED-R from the accumulated CED-NR, the total CED of RSCC is about 20 MJ higher compared to the total CED of WCCC.

3. Discussion and Summary

The life cycle inventory incorporates uncertainties and is simplified in comparison to reality. The non-specificity of the absolute results is caused by the use of generic data sets, such as those for transports and end-of-life scenarios. Since the weather and willow cultivation are unpredictable, we used average values for willow production from the previous decades. Additionally, in order to make a valid conclusion about fertilizers' use in the growing and formation of willow rods, mechanical qualities must be researched and quantities need to be determined. The manufacture of prototypes is limited in terms of industrial upscaling (learning curves, synergistic effects). Furthermore infrastructure, facilities and packing are not covered. Due to uncertainty and lack of data, electricity used for recycling the WCCC elements is neglected.

Nonetheless, the comparative claims hold true because the ceilings are assessed using the same database or comparable non-specific datasets, along with the same assessment categories and methodologies.

It is worth to mention, a simplified LCA can overlook problem shifting issues which can be met by including further environmental impact categories and an extended comparison of WCCC with other commercially available e.g. (partly-)biobased timber ceilings. Thus, future research should address a comparative economic and social assessment to complete a sustainability assessment.

The WCCC under investigation demonstrated that low-impact and circular materials form the cornerstone of a sustainable construction industry. The WCCC's competitiveness against reinforced steel concrete ceiling (RSCC) element is heavily reliant on material and production efficiency improvements. In this case study the WCCC already beats the RSCC within the investigated environmental impact categories. Weight- and material efficiency are crucial for transportation and energy recovery and biomass recycling reduces the climate change impact, even though it involves tradeoffs regarding the carbon cycle. Further improvements due to up scaling can be expected when lighter constructions and more efficient production techniques are included into future designs to further optimize this new type of ceiling structure.

Acknowledgements

- Funding

This work was supported by the Ministry of Food, Rural Affairs and Consumer Protection Baden-Württemberg within the research project “ReGrow – Funktionsintegrierter Leichtbau für nachhaltiges Bauen mit regional nachwachsenden Rohstoffen [Functionally integrated lightweight construction for sustainable building with regionally renewable raw materials]” (funding code: BWBF110032) and the research project WillowWeave (funded by the Strategy fund of Karlsruhe Institute of Technology). The responsibility for the content of this publication lies with the authors.

- Authors

Steffl: Conceptualization, Data curation, Experimental Design, Data- & Formal analysis, Investigation, Methodology, Writing-original draft, Writing-review & editing
Volk: Supervision, Resources, Writing-original draft, Writing-review & editing
Dörstelmann: Resources, Investigation, Writing-review & editing
Schultmann: Supervision, Writing-review & editing

4. References

1. Mathur VK. Composite materials from local resources. *Construction and Building Materials.* 2006;20:470–7. doi:10.1016/j.conbuildmat.2005.01.031.
2. Fernandez JE. Material architecture: Emergent materials for innovative buildings and ecological construction. Amsterdam: Elsevier/Architectural Press; ISBN 9780750664974, 2006.
3. Lawrence M. Reducing the Environmental Impact of Construction by Using Renewable Materials. *j renew mater.* 2015;3:163–74. doi:10.7569/JRM.2015.634105.
4. Weidner S, Mrzigod A, Bechmann R, Sobek W. Graue Emissionen im Bauwesen – Bestandsaufnahme und Optimierungsstrategien. [Grey emissions in construction - Inventory and optimization strategies]. *Beton und Stahlbetonbau.* 2021;116:969–77. doi:10.1002/best.202100065.
5. Santos GZBd, Caldas LR, Melo Filho JdA, Monteiro NBR, Rafael SIM, Da Marques Silva N. Circular alternatives in the construction industry: An environmental performance assessment of

sisal fiber-reinforced composites. *Journal of Building Engineering.* 2022;54:104603. doi:10.1016/j.jobe.2022.104603.

6. Hailemariam EK, Hailemariam LM, Amede EA, Nuramo DA. Identification of barriers, benefits and opportunities of using bamboo materials for structural purposes. *ECAM.* 2023;30:2716–38. doi:10.1108/ECAM-11-2021-0996.
7. Achenbach H, Rüter S. Ökobilanz-Daten für die Erstellung von Fertighäusern in Holzbauweise. [Life cycle assessment data for the construction of prefabricated houses in timber construction]. Braunschweig: Johann Heinrich von Thünen-Institut; 2016. http://hdl.handle.net/10419/129672 (accessed: 05 July 2024).
8. Rüter S, Diederichs Stefan. Ökobilanz-Basisdaten für Bauprodukte aus Holz. [Basic life cycle assessment data for wooden construction products]; 2012. https://literatur.thuenen.de/digbib_extern/dn050490.pdf (accessed: 05 July 2024).
9. Werner F, Richter K. Wooden building products in comparative LCA. *Int J Life Cycle Assess.* 2007;12:470–9. doi:10.1065/lca2007.04.317.
10. Quintana-Gallardo A, Schau EM, Niemelä EP, Burnard MD. Comparing the environmental impacts of wooden buildings in Spain, Slovenia, and Germany. *Journal of Cleaner Production.* 2021;329:129587. doi:10.1016/j.jclepro.2021.129587.
11. Roswag-Klinge E, Neumann E, Klinge A. Climate impacts of wood/ timber as a building material – investigated on three urban quarters in Germany (CIW). *IOP Conf. Ser.: Earth Environ. Sci.* 2022;1078:12029. doi:10.1088/1755-1315/1078/1/012029.
12. Rinne R, Ilgın HE, Karjalainen M. Comparative Study on Life-Cycle Assessment and Carbon Footprint of Hybrid, Concrete and Timber Apartment Buildings in Finland. *Int J Environ Res Public Health* 2022. doi:10.3390/ijerph19020774.
13. Beck-O'Brian M, Egenolf V, Winter S, Zahnen J, Griesshammer N, Bringezu S. Everything-from-wood: The resource of the future or the next crisis; 2022. https://www.wwf.de/fileadmin/fm-wwf/Publikationen-PDF/Wald/WWF-Study-Everything-from-wood.pdf (accessed: 05 July 2024).
14. Liang S, Gu H, Bergman R, Kelley SS. Comparative life-cycle assessment of a mass timber building and concrete alternative. *WFS.* 2020;52:217–29. doi:10.22382/wfs-2020-019.
15. Bärwolff M, Hansen H, Hofmann M, Setzer F. Energieholz aus der Landwirtschaft. [Energy wood from agriculture]. 2012. https://www.nw-fva.de/fileadmin/nwfva/publikationen/pdf/barwolff_2012_energieholz_aus_der.pdf (accessed: 05 July 2024).
16. González-García S, Mola-Yudego B, Murphy RJ. Life cycle assessment of potential energy uses for short rotation willow biomass in Sweden. *Int J Life Cycle Assess.* 2013;18:783–95. doi:10.1007/s11367-012-0536-2.
17. Schweier J, Schnitzler J-P, Becker G. Selected environmental impacts of the technical production of wood chips from poplar short rotation coppice on marginal land. *Biomass and Bioenergy.* 2016;85:235–42. doi:10.1016/j.biombioe.2015.12.018.
18. Burger FJ. Bewirtschaftung und Ökobilanzierung von Kurzumtriebsplantagen [Dissertation]: Technische Universität München; 2011, https://d-nb.info/1010256432/34 (accessed: 05 July 2024).
19. M&T Heid GbR. Production of willow rods. Interview by Simon Steffl. 20 Apr. 2023.
20. Ben-Alon L, Loftness V, Harries KA, Cochran Hameen E. Life cycle assessment (LCA) of natural vs conventional building assemblies. *Renewable and Sustainable Energy Reviews.* 2021;144:110951. doi:10.1016/j.rser.2021.110951.

21. Picuno P. Use of traditional material in farm buildings for a sustainable rural environment. *International Journal of Sustainable Built Environment.* 2016;5:451–60. doi:10.1016/j.ijsbe.2016.05.005.

22. Ben-Alon L, Loftness V, Harries KA, DiPietro G, Hameen EC. Cradle to site Life Cycle Assessment (LCA) of natural vs conventional building materials: A case study on cob earthen material. *Building and Environment.* 2019;160:106150. doi:10.1016/j.buildenv.2019.05.028.

23. Ventura A, Ouellet-Plamondon C, Röck M, Hecht T, Roy V, Higuera P, et al. Environmental Potential of Earth-Based Building Materials: Key Facts and Issues from a Life Cycle Assessment Perspective;2021:261–96. doi:10.1007/978-3-030-83297-1_8.

24. Schroeder H. Muster-Umweltproduktdeklaration Lehmputzmörtel. [Environmental Product Declaration on flush mounted clay]; 2023. https://www.dachverband-lehm.de/file_download/166/DVL_UPD_LPM_U11.pdf (accessed: 05 July 2024).

25. Deutsches Institut für Normung e.V. DIN EN 15804-2022-03 Nachhaltigkeit von Bauwerken - Umweltproduktdeklarationen: Grundregeln für die Produktkategorie Bauprodukte. [Sustainability of construction works Environmental products declaration core rules for the product category of construction products] March 2022; 91.010.99; 91.040.01.

26. DIN EN. Eurocode 1: Einwirkungen auf Tragwerke: Teil 1-1 Allgemeine Einwirkungen auf Tragwerke; Wichte von Baustoffen und Lagergütern, Eigengewicht und Nutzlasten im Hochbau. [Eurocode 1: Actions on structures - Part 1-1: Specific weight of materials, self-weight of construction works and imposed loads on buildings] 1991-1-1:2023;91.010.30. Berlin: Beuth Verlag GmbH.

27. Nakatani J. Life Cycle Inventory Analysis of Recycling: Mathematical and Graphical Frameworks. *Sustainability.* 2014;6:6158–69. doi:10.3390/su6096158.

28. Roedl Anne. Ökobilanzierung der Holzproduktion im Kurzumtrieb. [Life Cycle Assessment of short coppice wood production]; 2003. https://d-nb.info/1000170063/34 (accessed: 05 July 2024) https://d-nb.info/1010256432/34.

29. Nemecek T, Kägi T. Life Cycle inventories of agricultural production systems; 2007. https://www.researchgate.net/profile/Thomas-Nemecek/publication/263239333_Life_Cycle_Inventories_of_Agricultural_Production_Systems/links/5ed5eeaf299bf1c67d32894d/Life-Cycle-Inventories-of-Agricultural-Production-Systems.pdf. (accessed: 05 July 2024)

30. Flamme S, Hanewinkel J, Quicker P, Weber K. Energieerzeugung aus Abfällen Stand und Potenziale in Deutschland bis 2030. [Energy generation from waste Status and potential in Germany up to 2030]; 2018. https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2018-06-26_texte_51-2018_energieerzeugung-abfaelle.pdf (accessed: 05 July 2024).