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APPLYING LIFE CYCLE ASSESSMENT WITH MINIMAL INFORMATION TO SUPPORT EARLY-STAGE MATERIAL SELECTION

Matthew Roberts*, Valeria Cascione, Stephen Allen, Barrie Dams, Daniel Maskell, David Coley

University of Bath, Faculty of Engineering and Design, Department of Architecture and Civil Engineering, Claverton Down, BA2 7AY Bath, United Kingdom

* corresponding author: `mar90@bath.ac.uk`

Abstract. Traditional life cycle assessment (LCA) is too data intensive and time consuming to be used during typical building design processes. Conducting an LCA during the building design process therefore requires simplifications and assumptions. Such "screening LCAs" are quicker and can be used with less data but introduce greater uncertainty. Unfortunately, uncertainty is not reflected in standard deterministic LCA calculations, which produce single-point values in LCA results. Thus, in this study, data quality scoring has been incorporated into a screening LCA to produce probabilistic predictions of environmental performance based on limited data. The approach has been applied during the design process of a bio-based wall panel designed for a circular economy. A combination of ecoinvent and material data sheets were used to analyse a wide range of novel bio-based insulation materials. The screening LCA analysed global warming potential and identified a short-list of promising materials that were then subjected to a detailed LCA for further consideration in the design. The method uses publicly available information and can be applied at material or building-element level. The method thus helps designers estimate environmental impacts without hindering the design process.

Keywords: Life cycle assessment, bio-based materials, circular economy, uncertainty.

1. Introduction

The timing of emissions associated with construction is significant when considering how to mitigate climate change [1]. The production of materials, needed for building construction and renovation, contributed 11 % of global energy-related CO_2 emissions in 2017 [2]. Unlike operational impacts, which occur over an extended period, upfront embodied impacts have already occurred by the time a building has been constructed and, therefore, represent the immediate impacts of a building [3]. Decisions that occur during the design process greatly influence the magnitude of these embodied impacts. Within the UK, the building design process is standardised by the Royal Institute of British Architects (RIBA) Plan of Work [4]. The RIBA Plan of Work classifies the design process into 8 stages, including: two pre-design stages, three design stages and construction, handover, and use stages [4]. As the design progresses, the ability to influence the design with ease diminishes [5]. This is due to the elimination of design variants and the selection of characteristics and materials. Early-stage design decisions have a large influence on the overall environmental performance of a design. When appropriate considerations are taken, the design process can be guided to low-impact solutions that produce the most environmentally beneficial outcome [1, 6]. Frequently, designers rely on past experience to evaluate between alternatives [7]. This approach does not guarantee that the best solution is taken and can perpetuate the selection of sub-optimal design solutions; thus, producing environmental impacts that would be avoidable.

Life cycle assessment (LCA) is an internationally recognized means of assessing the environmental impacts that occur throughout all stages of a product's, or system's, life cycle [8]. When implemented effectively, LCA can be used to support the selection of environmentally beneficial solutions [9]. Unfortunately, LCA is typically perceived to be too time consuming and data intensive to be compatible with the nuances of early-stage design [10, 11]. Therefore, LCA is often only implemented late in the design process when little is expected to change [12, 13]. This relegates LCA to being an accountancy tool that, generally, is used for green building certification schemes [14, 15]. Screening LCAs (SLCAs) have emerged as a means of providing a relatively quick assessment [16]. SLCAs are, however, characterised by elevated levels of uncertainty that can devalue their conclusions [17]. SLCAs can be used to simplify the level of detail in the life cycle inventory and the scope of the impact assessment method [18]. The challenges of assessing materials, or design variants, in the design process are amplified when unconventional materials or materials with limited information are considered.

The use of bio-based materials to substitute traditional, more impactful, materials has been proposed as one means of lowering the impacts attributed to material use in the built environment [19]. Bio-based materials sequester atmospheric carbon as they grow and, typically, have low processing impacts when compared to other construction materials [20]. The sequestered carbon is stored within the bio-based materials until end-of-life when a proportion of the sequestered carbon is emitted to atmosphere [20, 21]. The use of bio-based materials provides additional benefits within the context of a circular economy [22]. The concept of a circular economy is focused on the retention of materials in the value chain to minimise raw material extraction and eliminate the production of waste [23]. For bio-based materials that are designed to be circular, the sequestered carbon is stored within the material for the duration that it is retained in the value chain [20, 21]. Therefore, the more circular a bio-based product is, the longer the release of sequestered carbon is postponed.

The present study uses data quality to incorporate uncertainty into a SLCA to improve the confidence in the conclusions that can be drawn from this type of assessment. The approach has been applied to the design of a circular economy bio-based external wall assembly. This study has been conducted to demonstrate how LCA can be used as a decision support tool while dealing with inadequate levels of information needed for a traditional LCA.

2. METHODS

The assessment discussed in this paper is categorised by two distinct phases: (1) an initial SLCA; (2) a detailed LCA of specific materials identified from the SLCA. The SLCA was done when there was a lack of available data for the assessed materials, a common obstacle faced during the design process, whilst the detailed LCA was performed for materials once whole processes and required data was available. The goal of the SLCA was to identify which materials should be subjected to a detailed LCA based on what their environmental performance is likely to be. The SLCA did not try to quantify the exact environmental impacts of each material. Data quality has been considered in the SLCA to visualise the uncertainty associated with the calculated impacts. The SLCA was limited to raw material supply (A1) and product stage transport (A2) [24] due to the availability of information for the assessed materials. Product stage manufacturing (A3) was not included within the scope of the SLCA due to the lack of available data for the assessed materials. The materials were compared based on their anticipated ranges of impacts. After the SLCA, two materials were identified and were subjected to a detailed LCA for A1–A3.

2.1. DATA QUALITY

For the purposes of this SLCA, only publicly accessible information was used. The use of publicly accessible information was chosen to enable life cycle thinking to support the design process even if information is sub-optimal and/or has significant gaps. A combination of publicly available material specifications and articles were used for this study.

The use of sub-optimal data introduces various sources of uncertainty and makes data quality very relevant to the types of conclusions that can be made. Data quality assessment provide a means to visualise and communicate uncertainty, aiding the process of comparing multiple materials when the level of detail for each varies. The ecoinvent 3.0 pedigree matrix, as presented in Ciroth et al. [25], has been used to assign data quality indicators for each of the assessed materials based on reliability; completeness; temporal correlation; geographic correlation; and, further technological correlation. The pedigree matrix is used to assign a value between 1–5, with 1 having the least uncertainty and 5 having the most uncertainty, to each indicator that reflects how well the information represents the assessed system. The data quality indicators are converted into uncertainty factors following Table 10.5 from Weidema et al. [26]. These uncertainty factors have been combined with a basic uncertainty of 0.04 (Table 10.3, Weidema et al. [26]) to get the standard deviation for each material by using Equation (1). The basic uncertainty is used to capture the variances associated with representing the values as a normal distribution [26]. It is important to note that Equation (1) functions under the assumption that each variance is normally distributed and independent.

$$\sigma = \sqrt{\sum_{n=1}^{6} \sigma_n^2}, \tag{1}$$

where σ_1^2 represents the basic uncertainty and σ_{2-6}^2 represent the variance for each indicator score

2.2. IMPACT ASSESSMENT

The EuGeos 15804+A2 v4.1, an extension to the ecoinvent version 3.6 database, has been used to determine the environmental impacts of the constituent components of each assessed material. However, any database that includes detailed environmental impacts for individual materials could be used to conduct a similar assessment. For this study, the global warming potential evaluated over a 100-year time horizon (GWP_{100}) has been used to compare the materials against one another. The total GWP_{100}, including biogenic carbon storage, is reported for the SLCA results of each assessed material.

3. CASE STUDY

The presented approach has been applied to the selection of insulation materials for the design of an external wall assembly. The design of the wall assembly in question is described in Cascione et al. [35]. A SLCA was conducted to compare multiple materials under consideration for improved design iterations and identify materials that would likely provide the most favourable environmental performance based on

Material	Density [kg/m^3]	λ [W/mk]	Constituent Material Breakdown	References
Mycelium	95	0.08	Pleurotus Ostreatus, straw, flour, corn, wheat	[27], [28]
Recycled Cotton	20	0.039	Cotton, recycled fibre, polymer binder	[29]
Compressed Reed	275	0.052	Typha, magnesite	[30]
Agriculture Fibre	30	0.038	Fibres (cotton, flax, hemp), polyethylene (PE) binder, fungicide	[31]
Cellulose Wadding	45	0.04	Cellulose wadding, hemp, PE binder	[31]
Grass Fibre	40	0.04	Grass fibre, recycled fibres, polyester	[32]
Flax	23	0.035	Flax, polyester binder, salts	[33]
Sheep’s Wool	25	0.035	Sheep’s wool, bicomponent polyester	[34]

Table 1. Key characteristics for the assessed bio-based insulation materials.

Material	Reliability	Completeness	Temporal Correlation	Geographic Correlation	Further Technological Correlation	Standard Deviation (σ)
Mycelium	0.002	0.002	0	$2.5 \cdot 10^{-5}$	0.008	0.228
Recycled Cotton	0.0006	0	0.0002	$2.5 \cdot 10^{-5}$	0.008	0.221
Compressed Reed	0.002	0.002	0.002	$2.5 \cdot 10^{-5}$	0.008	0.232
Agriculture Fibre	0.0006	0.0006	0.0002	$2.5 \cdot 10^{-5}$	0.008	0.222
Cellulose Wadding	0.0006	0.0001	0	$2.5 \cdot 10^{-5}$	0.04	0.284
Grass Fibre	0	0	0	$2.5 \cdot 10^{-5}$	0.0006	0.202
Flax	0	0.0001	0	$2.5 \cdot 10^{-5}$	0.0006	0.202
Sheep’s Wool	0.0006	0.0006	0.0002	$2.5 \cdot 10^{-5}$	0.008	0.221

Table 2. Assigned variances (σ^2) based on pedigree matrix scores with calculated standard deviation.

a limited amount of information. The density, thermal conductivity (λ) and material breakdown of each assessed insulation are included in Table 1. The references included in Table 1 were used to gather the constituent material composition information needed to conduct the SLCA. As the study considers novel bio-based materials, there were no environmental product declarations (EPDs) available. EPDs are typically prepared for established and mass-produced materials to describe the environmental impacts that are anticipated to occur throughout the material’s life cycle.

The SLCA was carried out for all materials under consideration for future design iterations. Data quality indicator scores were assigned, following the pedigree matrix [25], based on the quality of information available for each material. These data quality scores were used to assign variances for each data quality indicator which were then combined with the basic uncertainty to acquire the standard deviation based on Equation (1). Table 2 summarises the assigned variances and standard deviations for each of the assessed materials. Based off the pedigree matrix method used, higher variances are associated with more uncertain results and correspond to higher standard deviations. Variances with an assigned value of 0 demonstrate the highest level of confidence in the information used to conduct the assessment.

4. RESULTS

The assessment has been conducted in two parts to capture the thermal resistance and assembly thickness of the first design iteration [35]. The first comparison is conducted for the desired R-value of 6.3 m^{2}K/W and an unrestricted insulation thickness. Table 3 presents the expected ranges of A1–A2 GWP$_{100}$ for each material when the desired R-value is achieved. Most materials meet the desired R-value with a thickness of ∼300 mm. Mycelium and compressed reed insulation require thicknesses of 510 mm and 365 mm, respectively, to provide the desired thermal resistance. It is important to note that the required thickness of mycelium will have further implications on the wall panel design as it would require additional stud framing and fasteners to house the insulation, thus increasing material usage. These knock-on impacts of increased insulation thicknesses are not discussed within the scope of this paper.

A second comparison was completed with an insulation thickness limited to a maximum of 300 mm, matching the wall assembly thickness of the first design iteration [35]. The ranges of expected A1–A2 Total GWP$_{100}$, depicted by probability density func-

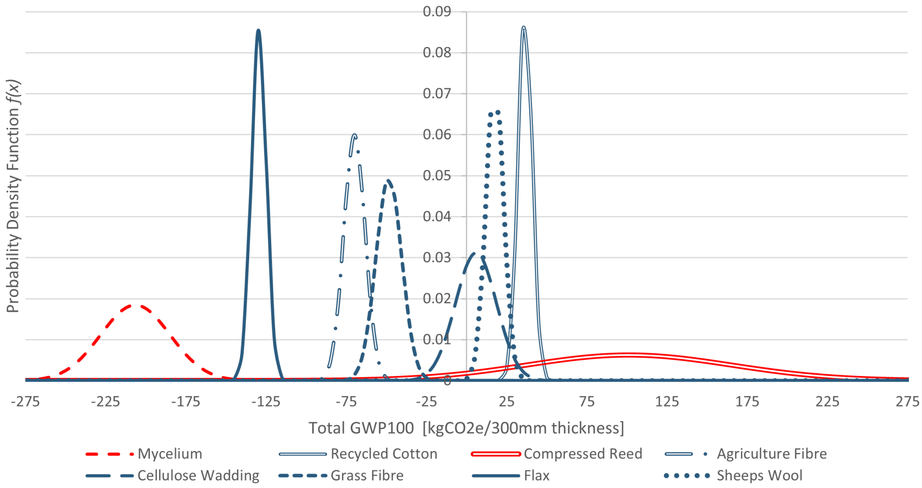

Figure 1. SLCA (A1–A2) Total GWP$_1$00 results for 300 mm insulation thickness (R-values vary).

Material	Required Thickness [mm]	A1–A2 Total GWP100 [kg CO_2e]		
		-3 Standard Deviations	Median Value	+3 Standard Deviations
Mycelium	510	-416.1	-351.1	-286.1
Recycled Cotton	300	23.2	36.5	49.8
Compressed Reed	365	-68.8	123.0	314.7
Agriculture Fibre	300	-90.0	-70.0	-50.0
Cellulose Wadding	310	-32.3	6.1	44.4
Grass Fibre	310	-52.1	-27.9	-3.7
Flax	280	-134.8	-120.8	-106.9
Sheep's Wool	280	-0.3	16.3	32.9

Table 3. Expected SLCA GWP$_1$00 ranges and required thickness for thermal resistance of 6.3 m^2K/W.

tions, are presented in Figure 1 for each material. Under the 300 mm wall thickness, mycelium and the compressed reed insulations did not meet the required thermal resistance as they were only able to reach thermal resistances of 4 m^2K/W and 5.3 m^2K/W, respectively.

5. Discussion

Table 3 and Figure 1 clearly convey how the certainty of GWP$_{100}$ results is affected by variance in the underlying data quality of each material. This is much more transparent than the typical approach of presenting single-point estimates and rankings, which implies all values are equally certain. A negative total GWP$_{100}$ indicates that the amount of sequestered carbon outweighs the fossil impacts of acquiring the constituent materials in A1–A2. The Total GWP$_{100}$ for mycelium and compressed reed display the greatest difference when their expected ranges are compared between Table 3 and Figure 1.

Based on Table 3 and Figure 1, the materials that are most likely to provide environmentally beneficial results are mycelium and the flax based insulations. The distributions for agricultural fibre mix and grass fibre insulations have some overlap when compared at a 300 mm thickness, but the expected ranges for both are separate from other considered materials. The expected range for the cellulose wadding insulation encompasses that of the sheep's wool insulation in its entirety. From the SLCA, it would be impractical to make conclusions between these materials due to the significant overlaps present in their respective distributions. The compressed reed insulation presents a very wide range of possible values, most of which are at the highest end of GWP results. The compressed reed insulation should not be included within the design considerations based on the information available.

5.1. Comparison against Detailed LCA

Following the SLCA, a detailed LCA was conducted for A1–A3 for both the mycelium and flax based insulations. A combination of manufacturer information, material specifications and published literature was used to complete the detailed assessment. The full life cycle inventories (LCIs) for the detailed LCAs of mycelium and flax based insulations are included within the supplemental materials of the study by Cascione et al. [36]. The results for the SLCA are

Material	Required Thickness [mm]	SLCA [A1-A2] Total GWP_{100}			[A1-A3] GWP_{100}			
		-3 σ	Median	+3 σ	Total	Biogenic	Fossil	LULUC
Mycelium	510	-446.1	-348.5	-250.9	-181.2	-738.8	557.6	0.89
Flax	280	-131.4	-120.3	-109.2	-105.5	-155.4	50.0	0.06

TABLE 4. Comparison between SLCA (A1–A2) and detailed LCA (A1–A3) results in kg CO_2e.

compared against that of the detailed LCA in Table 4. The values presented in Table 4 represent the environmental impact needed to produce enough material to meet the desired thermal resistance of 6.3 m^2K/W.

To meet the desired thermal resistance of 6.3 m^2K/W, 510 mm of mycelium or 280 mm of flax would be required as previously mentioned. The results from the detailed LCA are higher than expected SLCA ranges presented in Figure 1 due to the inclusion of process impacts needed in the manufacturing (A3) life cycle stage. Since the sequestered carbon may be emitted at end-of-life, it is important to consider the Fossil GWP_{100} as it indicates an immediate emission of greenhouse gases. In order to reduce the environmental impacts of the built environment, materials with minimal Fossil GWP_{100} impacts should be prioritised. As shown in Table 4, the Fossil GWP_{100} impacts for mycelium are 557.6 kg CO_2e for the required thickness due to the energy required during the manufacturing processes [37]. The Fossil GWP_{100} for the mycelium insulation is 11 times higher than the Fossil GWP_{100} for the flax based insulation. Based on the detailed LCA, the flax insulation provides a high performing bio-based insulation alternative with minimal A1–A3 Fossil GWP_{100} impacts and therefore would be more environmentally favourable than the mycelium insulation.

6. CONCLUSIONS

The use of LCA during early-stage material selection is often hindered by insufficient information and constrained project timelines. The use of screening LCAs (SLCAs) can reduce the time needed to conduct an assessment but can introduce an increased level of uncertainty. In this study, a pedigree matrix approach is used in a SLCA methodology to calculate a probability distribution for global warming potential and estimate the uncertainty caused by variations in data quality. This is more transparent than the typical approach of presenting single-point estimates and rankings, which implies all values are equally certain. The approach has been applied during the design process of a bio-based wall panel for a circular economy. This was done to identify insulation materials that were likely to result in a low environmental impact while mitigating challenges associated with information gaps during early design material selection. The SLCA only considered A1–A2. There is scope to incorporate additional life cycle considerations into the assessment, including transportation, product lifespan, and end-of-life. The inclusion of uncertainty highlighted that there was no clear ranking among some materials since their probability distributions of global warming potential exhibited significant overlaps. For the materials subjected to the detailed LCA, the SLCA scope (A1–A2) gave a reasonable indication of A1–A3 impacts for flax based insulation, since it did not have large processing impacts in A3. The mycelium insulation was found to have significant A3 impacts. SLCAs enable a multitude of materials to be considered prior to the completion of a detailed LCA for materials that perform favourably in the SLCA.

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REFERENCES

[1] L. Strain. Time value of carbon. Carbon Leadership Forum, Seattle, 2017.

[2] International Energy Agency. Material efficiency in clean energy transitions. Paris, 2019. `https://doi.org/10.1787/aeaaccd8-en`

[3] WorldGBC. Bringing embodied carbon upfront. London; Toronto, 2019, [2019-11-15]. `https://www.worldgbc.org/sites/default/files/WorldGBC_Bringing_Embodied_Carbon_Upfront.pdf`

[4] RIBA. Plan of work 2020. RIBA, London, 2020.

[5] HM Treasury. Infrastructure carbon review. London, 2013, [2020-06-06]. `https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/260710/infrastructure_carbon_review_251113.pdf`

[6] M. Erlandsson, M. Borg. Generic LCA-methodology applicable for buildings, constructions and operation services – today practice and development needs. *Building and Environment* **38**(7):919–938, 2003. `https://doi.org/10.1016/S0360-1323(03)00031-3`

[7] Y. Chen, G. E. Okudan, D. R. Riley. Sustainable performance criteria for construction method selection in concrete buildings. *Automation in Construction* **19**(2):235–244, 2010. `https://doi.org/10.1016/j.autcon.2009.10.004`

[8] CEN. BS EN ISO 14040:2006 Environmental management – Life cycle assessment – Principles and framework, 2006.

[9] E. Meex, A. Hollberg, E. Knapen, et al. Requirements for applying LCA-based environmental impact assessment tools in the early stages of building design. *Building and Environment* **133**:228–236, 2018. `https://doi.org/10.1016/j.buildenv.2018.02.016`

[10] A. Hollberg, J. Ruth. LCA in architectural design – a parametric approach. *The International Journal of Life Cycle Assessment* **21**(7):943–960, 2016. `https://doi.org/10.1007/s11367-016-1065-1`

[11] T. Jusselme, E. Rey, M. Andersen. Surveying the environmental life-cycle performance assessments: Practice and context at early building design stages. *Sustainable Cities and Society* **52**:101879, 2020. `https://doi.org/10.1016/j.scs.2019.101879`

[12] T. Lützkendorf. Assessing the environmental performance of buildings: trends, lessons and tensions. *Building Research & Information* **46**(5):594–614, 2018. `https://doi.org/10.1080/09613218.2017.1356126`

[13] M. Roberts, S. Allen, D. Coley. Life cycle assessment in the building design process – A systematic literature review. *Building and Environment* **185**:107274, 2020. `https://doi.org/10.1016/j.buildenv.2020.107274`

[14] G. Lamé, Y. Leroy, B. Yannou. Ecodesign tools in the construction sector: Analyzing usage inadequacies with designers' needs. *Journal of Cleaner Production* **148**:60–72, 2017. `https://doi.org/10.1016/j.jclepro.2017.01.173`

[15] T. Bruce-Hyrkäs, P. Pasanen, R. Castro. Overview of whole building life-cycle assessment for green building certification and ecodesign through industry surveys and interviews. *Procedia CIRP* **69**:178–183, 2018. `https://doi.org/10.1016/j.procir.2017.11.127`

[16] M. Budig, O. Heckmann, M. Hudert, et al. Computational screening – LCA tools for early design stages. *International Journal of Architectural Computing* **19**(1):6–22, 2021. `https://doi.org/10.1177/1478077120947996`

[17] C. Rodrigues, R. Kirchain, F. Freire, J. Gregory. Streamlined environmental and cost life-cycle approach for building thermal retrofits: A case of residential buildings in South European climates. *Journal of Cleaner Production* **172**:2625–2635, 2018. `https://doi.org/10.1016/j.jclepro.2017.11.148`

[18] M. D. Heidari, D. Mathis, P. Blanchet, B. Amor. Streamlined life cycle assessment of an innovative bio-based material in construction: A case study of a phase change material panel. *Forests* **10**(2):160, 2019. `https://doi.org/10.3390/f10020160`

[19] E. Resch, I. Andresen, F. Cherubini, H. Brattebø. Estimating dynamic climate change effects of material use in buildings – Timing, uncertainty, and emission sources. *Building and Environment* **187**:107399, 2021. `https://doi.org/10.1016/j.buildenv.2020.107399`

[20] B. Dams, D. Maskell, A. Shea, et al. A circular construction evaluation framework to promote designing for disassembly and adaptability. *Journal of Cleaner Production* **316**:128122, 2021. `https://doi.org/10.1016/j.jclepro.2021.128122`

[21] E. Hoxha, A. Passer, M. R. M. Saade, et al. Biogenic carbon in buildings: a critical overview of LCA methods. *Buildings and Cities* **1**(1):504–524, 2020. `https://doi.org/10.5334/bc.46`

[22] C. Mair, T. Stern. Cascading utilization of wood: a matter of circular economy? *Current Forestry Reports* **3**(4):281–295, 2017. `https://doi.org/10.1007/s40725-017-0067-y`

[23] Ellen MacArthur Foundation. Towards the circular economy: Economic and business rationale for an accelerated transition. Cowes, 2013.

[24] CEN. EN 15804:2012+A2:2019 – Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products. BSI, Brussels, 2020.

[25] A. Ciroth, S. Muller, B. Weidema, P. Lesage. Empirically based uncertainty factors for the pedigree matrix in ecoinvent. *The International Journal of Life Cycle Assessment* **21**(9):1338–1348, 2016. `https://doi.org/10.1007/s11367-013-0670-5`

[26] B. P. Weidema, C. Bauer, R. Hischier, et al. Overview and methodology. Data quality guideline for the ecoinvent database version 3. Ecoinvent report 1 (v3). St. Gallen: The ecoinvent Centre, 2013.

[27] Critical Concrete. Producing mycelium insulation, 2018. [2021-01-29]. `https://criticalconcrete.com/producing-mycelium-insulation/`

[28] M. Jones, A. Mautner, S. Luenco, et al. Engineered mycelium composite construction materials from fungal biorefineries: A critical review. *Materials & Design* **187**:108397, 2020. `https://doi.org/10.1016/j.matdes.2019.108397`

[29] LeRelais. Metisse l'isolation durable. Le Relais Metisse, Billy-Berclau, 2014.

[30] M. Krus, T. Werner, T. Großkinsky, G. Georgiev. A new load-bearing insulation material made of cattail. *Academic Journal of Civil Engineering* **33**(2):666–673, 2015. `https://doi.org/10.26168/icbbm2015.104`

[31] Biofib. L'isolation biosourcee, biofib, Sainte-Gemme-la-Plaine, 2020.

[32] GRAMITHERM. Fiche de déclaration environnementale et sanitaire GRAMITHERM® 150. Sambreville, 2021.

[33] Ecomerchant. Isovlas Flax-based insulation. Kent, [2021-08-04]. `https://www.greenspec.co.uk/green-products/timber-frame-floor-joist-zone-thermal-insulation/details/isovlas/humans.txt`

[34] Thermafleece. All the facts. Penrith.

[35] V. Cascione, M. Roberts, S. Allen, et al. Life cycle assessment of circular bio-based construction. In *4th International Conference on Bio-Based Buidling Materials*, pp. 1–9. 2021.

[36] V. Cascione, M. Roberts, S. Allen, et al. Integration of life cycle assessments (LCA) in circular bio-based wall panel design. *Journal of Cleaner Production* **344**:130938, 2022. `https://doi.org/10.1016/j.jclepro.2022.130938`

[37] E. Dorr, M. Koegler, B. Gabrielle, C. Aubry. Life cycle assessment of a circular, urban mushroom farm. *Journal of Cleaner Production* **288**:125668, 2021. `https://doi.org/10.1016/j.jclepro.2020.125668`