Life Cycle Assessment of HempWood® Natural Flooring

Third-Party Verified Report in Preparation for an Environmental Product Declaration

CONFIDENTIAL

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Prepared for

Fibonacci, LLC

By

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Acronyms and Definitions

EPD: Environmental Product Declaration

LCA: Life Cycle Assessment

LCI: Life Cycle Inventory

LCIA: Life Cycle Impact Assessment

PCR: Product Category Rule

1. Background and Introduction

Based in Murray, Kentucky, Fibonacci, LLC, specializes in engineered lumber made of hemp that is used for flooring and other building products. Fibonacci developed a hemp-based engineered lumber with the vision of creating a brighter future for the planet and stimulating American manufacturing by introducing sustainable building materials with a lower carbon footprint. Fibonacci's idea to use hemp was inspired by the use of bamboo, also a fast-growing sustainable wood product for flooring. Founder Greg Wilson and his development team worked to adapt the process of bamboo-based lumber production into one that utilizes different fast-growing plant species such as hemp, with the intention to provide a viable wood alternative that is more sustainable.

Fibonacci's signature product, HempWood® Natural Flooring, is a durable, low-VOC flooring product that is made with a no-added formaldehyde (NAF) soy-based adhesive. HempWood flooring is offered in three options: site-finished, Natural, and Custom Color Collection, which includes the choice of Espresso, Bourbon, Ice, Granite, Carbon, and Cherry. The Natural option is coated at the factory before shipment to customers. More information can be found at https://hempwood.com/.

As an environmental steward with the goal to present its products transparently, Fibonacci is producing a Type III Environmental Product Declaration (EPD) for HempWood Natural Flooring. An EPD provides straightforward information on a product's life cycle environmental performance for customers and the architecture/building community. An EPD is often used in support of the US Green Building Council's LEED certification program, specifically contributing points in the materials and resources section of LEED v.4.1.

The United Soybean Board provided funding to Omni Tech International, Ltd, who commissioned Four Elements Consulting, LLC, to perform an environmental Life Cycle Assessment (LCA) to develop the EPD. LCA has become one of the most valuable environmental tools for assessing the environmental footprint of a product or process, as it provides quantitative and scientific analyses of the environmental impacts of products and their associated industrial systems. Because it assesses each stage of the life of a product, LCA offers valuable information for a product's supply chain and helps to identify environmental attributes and weaknesses over the life cycle. Because LCA is a comprehensive assessment of the inputs and outputs of a product system, and because the LCA is externally verified, data and results can be used to develop publicly-available EPDs.

GOAL, INTENDED APPLICATIONS, AND INTENDED USERS

The goal of this study is to perform an ISO-compliant LCA from which to produce a Type III Environmental Product Declaration (EPD) in conformance with the International Organization for Standardization (ISO) 14025 standard.[1,2] The products are modeled with the guidance of the following Product Category Rules (PCRs):

- Main PCR: Part A: Product Category Rules for Building-Related Products and Services in: Brazil China India North America Southeast Asia, Adapted by UL Environment from the Institute Construction and Environment e.v. (IBU), Standard 10010, Version 4, dated March 28, 2022.[3,4]
- Subcategory PCR: Part B: Product Category Rules for Flooring EPD Requirements, UL 10010–7, Second Edition, dated September 28, 2018.[5,6]

The LCAs were performed in agreement with the requirements of the above PCRs with reference to EN 15804.[7]

Geographically, this study accounts for production of products at Fibonacci's Murray, KY, plant located at 301 Rockwood Rd., Murray, KY 42071. HempWood flooring is purchased and used primarily in North America.

This technical LCA report is intended to be internal to Fibonacci. The results and some of the information contained herein – after verification– will be used in the EPD which will be publicly-available. The information and data in the EPD are intended for business-to-business communication and may also be used for business-to-consumer communication.

EXTERNAL VERIFICATION

Because Fibonacci intends to use the results in a publicly-available EPD, this study will undergo external verification to ensure credibility and objectivity of the data and results as well as conformance with the standards on LCA and EPDs. The verification will ensure compliance with PCR Part A and the rules specifically set forth for flooring products in PCR Part B. The critical review process will also ensure the following:[8]

- "the methods used to carry out the LCA are consistent with this International Standard,
- the methods used to carry out the LCA are scientifically and technically valid,

[1] ISO 14044:2006/AMD 2:2020, Environmental management – Life cycle assessment – Requirements and guidelines – Amendment 2; ISO 14040:2006, the International Standard of the International Standardization Organization, Environmental management. Life cycle assessment. Principles and framework.
[2] ISO 14025:2006, Environmental labels and declarations – Type III – environmental declarations – Principles and procedures.
[3] This document specifies the calculation rules and reporting requirements for the underlying LCA reports used to inform EPDs in accordance with EN 15804. Hereinafter referred to as "PCR Part A".
[4] Hereinafter referred to as "PCR Part A".
[5] Hereinafter referred to as "PCR Part B".
[6] Note that this document predates ULE Part A v.4 and references ULE Part A v.3.2. Upon inspection of the changes, this does not affect any of the rules.
[7] EN 15804:2012+A1:2013, Sustainability of construction works -Environmental product declarations - Core rules for the product category of construction products.
[8] ISO 14044:2006, Section 6.1.

- the data used are appropriate and reasonable in relation to the goal of the study,
- the interpretations reflect the limitations identified and the goal of the study, and
- the study report is transparent and consistent."

2. Life Cycle Assessment Defined

LCA is a tool for the systematic evaluation of the environmental impacts of a product through all stages of its life cycle, which include extraction of raw materials, manufacturing, transport and use of products, and end-of-life management (e.g., recycling, reuse, and/or disposal). ISO developed principles and a framework for conducting LCA, and the four main parts of an LCA defined in this framework include:[9]

1. Goal and Scope definition: specifying the reason for conducting the study, intended use of study results, intended audience, system boundaries, data requirements, and study limitations.
2. Life Cycle Inventory (LCI): collecting, validating and aggregating input and output data to quantify material use, energy use, environmental discharges, and waste associated with each life cycle stage.
3. Life Cycle Impact Assessment (LCIA): using impact categories, category indicators, characterization models, equivalency factors, and weighting values to translate an inventory into potential impact on human health and the environment.
4. Interpretation: assessing whether results are in line with project goals, providing an unbiased summary of results, defining significant impacts, and recommending methods for reducing material use and environmental burdens.

This LCA adheres to the principles and framework in ISO 14040 as well as the guidelines specified in ISO 14044, as it pertains to the defined goals and scope.

3. System Boundaries

Product Studied

HempWood Natural Flooring is an engineered flooring product consisting of HempWood veneer adhered to hardwood plywood. Full-length fiber hemp stalks are sourced from local farmers. The stalks and fiber are broken apart and a soy-based adhesive is used to bind the hemp material. The material is compressed and baked to form HempWood lumber blocks. From the blocks, 4mm HempWood veneers are cut for the top layer of the flooring. The substrate is a 5-layer, 12-mm no added formaldehyde hardwood plywood manufactured by Columbia Forest Products (CFP). After adhering the veneer to the plywood, a tongue and groove profile is cut into the flooring. For this LCA, HempWood flooring is factory-coated using the more common Natural finish and is installed using nails, the most common installation method. The next table presents technical data for the product.

[9] ISO 14040:2006.

Table 1 HempWood Natural Flooring Technical Data

Name	Value
Flooring product thickness	0.63 in (16 mm)
Flooring product plank width	5 in (127 mm)
HempWood lumber density	1063 kg/m3[10]
CFP plywood density	500 kg/m3[11]
Finished flooring product weight	10.5 kg/m2

SYSTEM DESCRIPTION AND OVERALL SYSTEM BOUNDARY

The system boundaries have been modeled as "cradle-to-grave". This is depicted in the table below, in the context of the full life cycle as defined in EN 15804.[12]

Table 2 System Boundaries with Included and Excluded Product Stages

Production Stage			Installation Stage		Use Stage							End-of-Life Stage			
Extraction and upstream production	Transport to factory	Manufacturing	Transport to site	Installation	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	Deconstruction/Demolition	Transport waste processing or disposal	Waste processing	Disposal of waste
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4
X	X	X	X	X	MND	X	MND	X	MND	MND	MND	MND	X	MND	X

These modular life cycle components are briefly described below, with notes when a specific module is not included in this project, i.e., *"module not declared" (MND):*

- A1: production of materials used in the floor product and product packaging, Extraction of materials from the earth and/or extraction from post-consumer sources are quantified, if applicable. The purchased electricity in manufacturing is accounted for here.
- A2: transportation of those materials to the manufacturing facility.
- A3: manufacturing and assembly into the product and production of packaging materials.
- A4: delivery of the finished product to the building site.
- A5: installation of the product at the building site, plus processing of product waste and packaging waste.
- B1: impacts of the use of the product. *MND.*
- B2: the maintenance activities over the life of the product, such as vacuuming and sweeping.

[10] Data based on direct measurement by Fibonacci (May, 2022).
[11] Data based on direct measurement and confirmation by CFP representative (May, 2022 communications).
[12] EN 15804:2012+A1:2013 (E).

- B3: repair of the product. *MND.*
- B4: replacement of the product at the end of its reference service life (RSL). This includes production of new flooring (essentially, A1-A5 plus C1-C4 where applicable).
- B5: refurbishment of the product. *MND.*
- B6: energy use to operate the product. *MND.*
- B7: water use, if needed to operate the product. *MND.*
- C1: deconstruction impacts at end of its RSL. *MND.*
- C2: the transport of the product to its location of disposal or reprocessing at end of life (EOL).
- C3: any processing of waste before disposition. *MND.*
- C4: disposal of the waste, which accounts for the fate of the product, including disposal methods and recycling/reuse when applicable.
- D (not shown): Module D, benefits and loads, encompasses the avoided burdens associated with the product system, which may include activities related to recycling and/or reuse. *MND*.

Exclusions from the System Boundaries

Mentioned above, some of the modules in the Use Stage and End-of-Life Stage in Table 2 are not applicable to HempWood so are not included in the LCA. Additionally, production and disposal of capital equipment and human activities have been excluded. People involved in the production of flooring products do have a burden on the environment, such as driving to and from work. However, human activities are generally excluded from an LCA since it can be argued that these same people would still contribute to environmental factors whether or not they are contributing to the production of flooring products.

Function and Functional Unit, Product Lifetime

In order to conduct an ISO-compliant LCA, all flows within the system boundaries must be normalized to a unit summarizing the function of the system, enabling the calculation of the function on a quantitative basis, and in some cases, enabling the quantification of a comparison of products or systems on an equivalent basis. For this LCA and in accordance with the PCR, the function and functional unit have been defined as **1 m² of floor covering used in a building for a building estimated service life (ESL) of 75 years**. The mass of 1 m2 of flooring is 10.47 kg/m2 (

Table 1). HempWood flooring is used mainly in commercial spaces but may also be used in residential buildings.

The reference service life (RSL) of a product, or its quantified useful lifetime, is defined according to its declared technical and functional performance within a building.[13] HempWood flooring has an RSL of 25 years, based on the manufacturer warranty. This lifetime is consistent with general lifetime estimates of engineered wood floors of 20 to 30 years. The RSL applies to the in-use conditions in this LCA.

[13] EN 15804, sec. 6.3.3.

CUT-OFF CRITERIA

ISO 14044 requires a cut-off criterion to be defined for the selection of materials and processes to be included in the system boundary.
For this study and in accordance with the PCR,[14] the following has been adhered to:

- All efforts have been made to include all inputs and outputs to a (unit) process in the calculation.
- All known mass and energy flows have been reported; no known flows have been deliberately excluded. Every effort has been made to perform a comprehensive analysis on the production of these materials and the inclusion of energy.
- Data gaps have been filled by worst-case estimates with average or generic data. Any assumptions for such choices are documented in the Modeling and Assumptions section.
- Particular care has been taken to include material and energy flows known to have the potential to cause significant emissions into air and water or soil related to the environmental indicators of this standard.

RESULTS CATEGORIES

The first outcome of an LCA is the Life Cycle Inventory (LCI), i.e., the quantification of all elementary flows into and out of the systems studied. LCI results are classified into impact categories, that is, categories in which a set of related flows may contribute to impacts on environmental or human health. PCR Part A requires, at minimum, the impact categories presented in Table 3, and these are calculated using the North American (NA) methodology, Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) v.2.1.[15,16]

Table 3 LCIA Results Categories

Impact Category	Unit	Model Source (as provided in SimaPro)
Global warming potential (with biogenic C)	kg CO2-eq.	TRACI 2.1, using IPCC factors
Acidification potential	kg SO2-eq	TRACI 2.1
Eutrophication potential	kg N-eq.	TRACI 2.1
Ozone depletion potential	kg CFC11-eq.	TRACI 2.1
Photochemical smog formation potential (a.k.a. Smog creation potential)	kg O3-eq.	TRACI 2.1

TRACI 2.1 is considered scientifically and technically valid and is applicable to the NA geography. It is a recognized and accepted methodology to ensure a level playing field for use in EPDs. Table 4 lists the additional categories required for the EPD, as specified in PCR Part A.

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[14] PCR Part A, Sec. 2.9.
[15] UNITED STATES ENVIRONMENTAL PROTECTION AGENCY ORD/NRMRL/Sustainable Technology Division Systems Analysis Branch STD Standard Operating Procedure (SOP) SOP No. S-10637-OP-1-0 (2012) Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) Software Name and Version Number: TRACI version 2.1 USER’S MANUAL. Last updated November 2018 (version 1.05). For more information see the SimaPro Database manual Methods library.
[16] The impact method CML-IA, in conformance with ISO 15804, is not being reported as this study has a North American focus.

Table 4 LCI Results and Other Categories

Category	Unit	Model Source & Explanation
Resource Use: Energy		
Non-renewable primary energy used as an energy carrier (fuel)	MJ (LHV)	CED methodology.[17]
Non-renewable primary energy resources used as raw materials	MJ (LHV)	Calculated. Non-renew. energy of fossil-based raw materials in the product (eg, trad'l plastics)
Renewable primary energy used as an energy carrier (fuel)	MJ (LHV)	CED
Renewable primary energy resources used as raw materials	MJ (LHV)	Calculated. Renewable energy of biobased materials embodied in the product (eg, hemp)
Abiotic depletion potential for fossil resources	MJ	CML – baseline[18]
Resource use: Materials		
Secondary materials	Kg	Inventory. Materials used that have been recycled from another product system's use or its waste.
Renewable secondary fuels	MJ (LHV)	Inventory. Combustible material recovered from previous use or waste from another product system and used as a fuel in this system.
Non-renewable secondary fuels	MJ (LHV)	
Recovered energy	MJ	Energy recovered from waste of another product system. May include energy rec. from combustion of LF gas or other systems using energy sources.
Use of net fresh water (inputs minus outputs)	m3	Inventory.
Waste categories		
Non-hazardous waste disposed	Kg	EDIP 2003[19] & inventory
Hazardous waste disposed	Kg	EDIP 2003 & inventory
Radioactive waste disposed	Kg	EDIP 2003 & inventory. Includes high-level, intermediate-, and low-level.
Other output flows		
Components for reuse	Kg	Inventory.
Materials for recycling	Kg	Inventory.
Materials for energy recovery	Kg	Inventory. Energy recovery for another product system.
Recovered energy exported	MJ (LHV)	Inventory. Energy exported from this system and recovered, such as from waste inc. plants and LFs.

[17] CED is based on ecoinvent version 2.0 and has been expanded to include elements from the SimaPro database. Frischknecht R., Jungbluth N., et.al. (2003). Implementation of Life Cycle Impact Assessment Methods. Final report ecoinvent 2000, Swiss Centre for LCI. Dubendorf, CH, www.ecoinvent.ch. Recent adaptations to the method in 2018. See also www.pre.nl for more information.
[18] CML: CML-IA is a LCA methodology developed by the Center of Environmental Science (CML) of Leiden University in The Netherlands. More information at: http://cml.leiden.edu/software/data-cmlia.html. This method is an update of the CML 2 baseline 2000 and corresponds to the files published by CML in August 2016 (version 4.7).
[19] EDIP2003 is a Danish LCA methodology that is presented as an alternative to the EDIP97 methodology. The EDIP2003 version is adapted for SimaPro. Contact info: http://www.lca-center.dk/cms/site.aspx?p=4441.

Note: ISO 21930, section 7.2.11 requires the reporting of greenhouse gas emissions due to land-use change. Land use change is not significant for any of the systems in this study. Therefore, this metric is not included.

Category Descriptions
Global warming potential. The "greenhouse effect" refers to the ability of some atmospheric gases to absorb energy radiating from the earth, trapping the heat and resulting in an overall increase in temperature. Carbon dioxide, nitrous oxide, methane, and perfluorocarbon are examples of greenhouse gases. Since HempWood flooring contains more than 10% biogenic carbon, the GWP category is reported with biogenic CO2 equivalents. The GWP is calculated using factors from the 2021 Intercontinental Panel on Climate Change (IPCC) report.[20]

Acidification potential is the impact by which acidifying gases may dissolve in water (i.e., acid rain) or fix on solid particles and degrade or affect the health of vegetation, soil, building materials, animals, and humans.

Ozone depletion potential characterizes ozone depleting gases in product systems, which may include chlorofluorocarbons (CFCs or freons), halons, carbon tetrachloride, and trichloroethane. A decline in the ozone layer allows more harmful short wave radiation to reach the Earth's surface, potentially causing damage to human health, plants, and changes to ecosystems.

Photochemical smog formation potential (a.k.a. Smog creation potential) measures the potential for smog-forming gases that may produce photochemical oxidants.

Eutrophication Potential is the impact by which nutrient-rich compounds get into water bodies, resulting in a shift of species in an ecosystem and a potential reduction of ecosystem diversity. A common result of eutrophication is the rapid increase of algae, which depletes oxygen in the water and causes fish to die.

Non renewable fossil resources as abiotic resource depletion (ADP) refers to the depletion of fossil-derived non-renewable resources, including coal, oil, and natural gas. While this category is measured in MJ, it is not the energy use in the system; energy resources are reported as a separate set of flows.

Energy Resources measure the energy in the product system(s), including energy for upstream material extraction and production, through energy/fuel use at the assembly plant and the life cycle. It is also the energy embodied in raw materials, for example, hydrocarbons embodied in a plastic product. Non-renewable energy refers to the energy sources that are fossil-derived, including coal, oil, and natural gas, plus uranium consumed (i.e., at nuclear power production). Renewable energy may be biomass-based (wood or tree products or byproducts, agricultural byproducts) and other

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[20] IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change[Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, In press, doi:10.1017/9781009157896. Factors provided in SimaPro.

renewable sources, including wind, the sun, and geothermal. Energy is declared in MJ and is calculated based on lower heat value (LHV).

Material resources include the mass of renewable and non-renewable materials in the product systems. This category does not account for recovered or recycled materials within the same product system. These measures, declared in kg, are not the mass balance of the system; rather, they are the material resources extracted from the earth in the cradle-to-gate aggregated LCA data. Water use is *net* water used, and may include: evaporation (e.g. cooling towers), evapotranspiration (evaporation of irrigated water), embedded freshwater (e.g. concrete), and drainage of freshwater into the ocean.[21]

Waste. The non-hazardous and hazardous waste categories compile any waste reported by the manufacturer plus any waste in upstream materials production that might be reported as waste in production. The EDIP 2003 methodology captures the latter from the inventory output.

4. Software and Data Used

Commercially-available SimaPro LCA software was used to model the systems.[22] Both primary data (collected from the manufacturer) and secondary data (publicly-available, literature data) can be used for LCAs, and it is common to see a mix of both data types. For this study, Fibonacci supplied primary data on its bill of materials, manufacturing operations, and mode of transport to customers. Background data drew heavily from the DATASMART database;[23] the U.S. LCI database;[24] and the ecoinvent[25] database when the former two could not provide the data. Data on some materials were derived from publicly available, pertinent LCA studies, when available. The Data Quality section of this report addresses the quality of the data.

5. Product Modeling and Assumptions

Production Stage

Production stage includes modules A1 though A3, presented for HempWood flooring in the schematic below. These stages are described in the following subsections.

[21] PCR Part A, p.30
[22] PRé Consultants: *SimaPro 9.3 LCA Software*. 2020. The Netherlands.
[23] LTS. 2020. DATASMART LCI package, used from SimaPro; also found at http://ltsexperts.com/services/software/datasmart-life-cycle-inventory/.
[24] National Renewable Energy Laboratory (NREL): U.S. Life-Cycle Inventory Database. 2005. Golden, CO. Found at: http://www.nrel.gov/lci/database.
[25] Ecoinvent Centre, *Ecoinvent data v3.6* (Dübendorf: Swiss Centre for Life Cycle Inventories, 2019), retrieved from: www.ecoinvent.org.

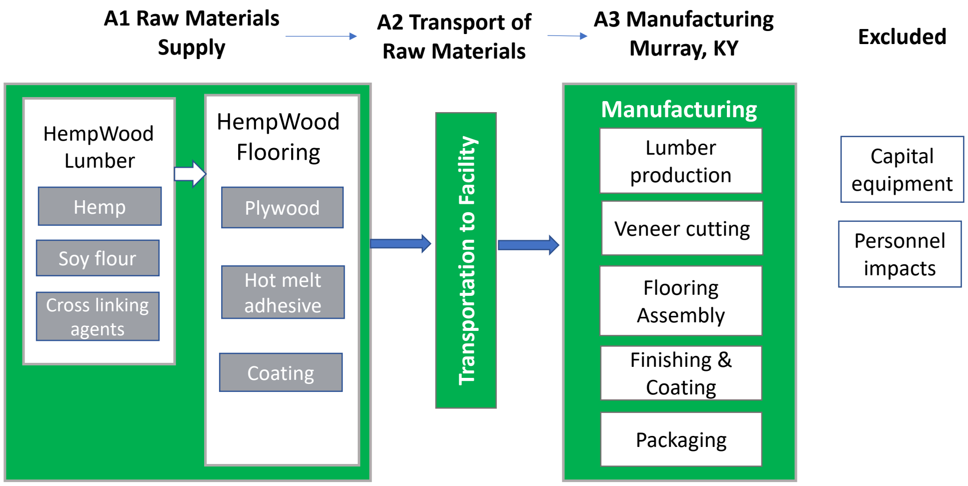

Figure 1 HempWood Flooring Production Stage

A1 Sourcing / Extraction

The following table presents the main materials in the flooring, their mass and percent contribution to the product, and the place of origin of the material.

Table 5 Bill of Materials – HempWood Flooring

Material or component	Quantity (% by weight)	Mass (kg/m2)	Distance to facility (mi)	Availability	
HempWood lumber	40.5%	4.25	Made on-site	Abundant	Renewable
Plywood	57.5%	6.0	519	Abundant	Renewable
Polyurethane hot melt adhesive	1%	0.11	450	Fossil limited	Non-renewable
Diacrylate coating	1%	0.11	500	Fossil limited	Non-renewable

HempWood Lumber Production

Full length hemp stalks, composed of outer bast fibers and inner woody hurd, are brought to the HempWood facility in bales. The bales are crushed and separated. They are gathered in 90-lb increments and spread evenly on mesh and submerged into a soy- and water-based adhesive system called Soyad. The saturated stalks are then dried, portioned out, and compressed under 3,000 tons of pressure into 5.5” by 5.5” by 72” molds. These are baked in an oven until the catalyst in the Soyad is activated and the lumber is set.[26] HempWood lumber consists of the following materials:

Table 6 Bill of Materials – HempWood Lumber

Material or component	% by weight	Distance to facility (mi)
Hemp	85%	40
Soy flour	11%	389
Cross Linking Agent (PAE)	2%	354
Cross Linking Agent (acrylic based)	2%	354

[26] YouTube video by Belinda Carr - https://www.youtube.com/watch?v=3Qy6awPeric.

Hemp

The crops purchased by Fibonacci for HempWood are dual purpose, i.e., harvested for both grain and fiber. Industrial hemp is grown for three main purposes, 1. flora for CBD oil from the flower (floral hemp), 2. fiber from the stalk for textiles, and 3. grain for oil/meal. A fundamental physical difference between floral hemp and hemp planted for fiber and grain is that floral hemp is planted with ample space so the plant grows short and stout, developing plentiful flower yields, while industrial hemp is planted close together, allowing denser biomass. The latter can grow 6-10 feet high. Hemp grown for fiber is not harvested for the hemp flower due to quality degradation of the stalk. As discussed in Westerhuis (2019), fibers are at their best quality when the stalk is harvested before flowering.[27]

Based on information from the manufacturer and confirmed in published documents,[28] an acre yields approximately 4,000 lbs stalk and 800 to 1000 lbs grain. Table 7 summarizes the agricultural inputs per acre. Hemp seedling and nutrient application rates are based on data in a report issued by the University of Kentucky Cooperative Extension Service.[29] Water use for germination and diesel fuel for operations from plowing to sowing, then cutting and harvesting, come from Zampori (2013).[30,31] No pesticides are allowed by law.

Table 7 Hemp Dual Purpose Crop Requirements

Material or component	Quantity per acre/yr	Notes
Seedlings	30-40 lb	Used 35 lb
Applied nitrogen	100 lb	
Available phosphorus	60 lb	
Available potassium	300 lb	
Diesel	156 kg	
Water	48.6 m3	

Because industrial hemp produces two viable products – grain and fiber from the stalks – an allocation for the growing and harvesting needed to be made, in order to assign the impacts attributed to what is used for the HempWood flooring system.[32] Since the hemp

[27] Westerhuis, W., *et.al*. Plant weight determines secondary fibre development in fibre hemp (Cannabis sativa L.). **Industrial Crops and Products** 139 (2019) 111493. Found at: https://doi.org/10.1016/j.indcrop.2019.111493

[28] Williams, D.W., *et al*., 2018 University of Kentucky Industrial Hemp Variety Trials for Dual-Purpose Production. Retrieved from: https://hemp.ca.uky.edu/sites/hemp.ca.uky.edu/files/2018_uk_dual-purpose_trial.pdf.

[29] University of Kentucky College of Agriculture, Food, and Environment, Cooperative Extension Service, 2018. An Introduction to Industrial Hemp and Hemp Agronomy, by D.W. Williams, Plant and Soil Sciences, and Rich Mundell, Kentucky Tobacco Research and Development Center. Table 1 - General agronomic recommendations for the main harvestable components of industrial hemp. Retrieved from: http://www2.ca.uky.edu/agcomm/pubs/ID/ID250/ID250.pdf.

[30] Zampori, Luca, et al., "Life Cycle Assessment of Hemp Cultivation and Use of Hemp-Based Thermal Insulator Materials in Buildings", Environ. Sci. Technol. 2013, 47, 13, 7413–7420.

[31] While Zampori (2013) is based on crops produced in the EU, it is used for lack of available other harvesting energy data. Their crop is similarly a dual purpose (for producing quality fiber output).

[32] Note that industrial hemp also produces flowers, but the flowers on these types of varietals are rarely, if ever, sold for use. Hemp plants grown for flowers are varietals that produce shorter, more leafy and flowery plants. The harvesting of these plants is done completely differently.

purchased for HempWood is not harvested for any flowers, flowers and their prices are excluded from the allocation.

In LCA, when allocation is necessary, the key to robust modeling is to determine the basis for the allocation (e.g., based on mass, economic value, etc.). ISO's preferred approach to allocation is as follows:[33]

1. Wherever possible, allocation should be <u>avoided</u> by:
   1) dividing the unit process to be allocated into two or more subprocesses and collecting the input and output data related to these subprocesses;
   2) expanding the product system to include the additional functions related to the co-products.

2. Where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way that reflects the underlying physical relationships between them.

3. Where physical relationship alone cannot be established or used as the basis for allocation, the inputs should be allocated between the products and functions in a way that reflects other relationships between them. For example, input and output data might be allocated between coproducts in proportion to the economic value of the products.

When LCA practitioners are faced with processes having coproducts, they defer to ISO's first preference, i.e., dividing the multiple output process into two or more subprocesses and avoiding allocation altogether. For hemp cultivation, this is not possible since the coproducts are grown together. Another option, expanding the system boundary, is not allowed for use in preparation for EPDs. Thus, the inputs and outputs are allocated based on physical partitioning. It made most sense to allocate based on the economic value of the coproducts, since fiber currently has a lower market use relative to hemp grain. More importantly, industrial hemp in the U.S. is currently being grown mainly for grain, as there is currently very little demand in the U.S. for hemp fiber. Table 8 summarizes the quantities by mass and their consistent average prices, which provides the calculation for the allocation percentages.[34] The appendix section provides more information on coproduct yields and the rationale for the price data used.

Table 8 Hemp Coproducts

	Output (lb/ac)	Alloc by Mass	Price/lb (avg)	Total value/ac	Alloc by Value	Notes
Hemp stalk (incl. fiber)	4000	81.6%	$0.075	$300	**29.2%**	Price data provided by Fibonacci, based on their suppliers. See appendix for more information.
Hemp grain	900	18.4%	$0.81	$729	**70.8%**	

[33] ISO 14044:2006, Section 4.3.4.2.
[34] It should be noted that PCR Part B calls for allocation by mass to be the default basis, but the difference in revenue is high enough, and the demand for one of the coproducts is low enough, to warrant using economic allocation.

Soy flour

Soy flour is produced by grinding defatted soybean meal flakes into a fine powder. The grinding energy of 0.207 MJ/kg flour came from calculations of Prater Industries (Illinois) grinding equipment.[35] Data for soybean production through soy oil and meal comes from a comprehensive 2009 peer reviewed study for USB published in the U.S. LCI database.[36] Other soy meal datasets were considered for this project, but this dataset appears to have still the most comprehensive and best quality production data despite the age.

Other HempWood lumber inputs

The soy flour is used in conjunction with the adhesive system, Soyad™, developed by Solenis. According to the Solenis website,[37] Soyad is a patented, bio-based, formaldehyde-free adhesive system used to produce hardwood plywood and engineered wood flooring. It is water-based and uses soy flour protein and a crosslinking resin. When blended together, the resin reacts with the protein to form a durable, water-resistant thermoset adhesive that is comparable in strength and performance to urea-formaldehyde-based adhesives traditionally found in wood products.

The cross-linking agent used in the Soyad system is assumed to be polyamide-epichlorohydrin (PAE) resin, based on a Solenis patent for Soyad.[38] PAE resin was built using stoichiometry of polyalkyleneamine and epichlorohydrin.[39] A dataset for polyacrylamide is used as a proxy for the polyalkyleneamine due to lack of available precise data for that amine. The other cross-linking agent used for HempWood lumber production is trimethylolpropane triacrylate (TMPTA). An acrylic acid dataset was used for this. See

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[35] Prater Industries M101 Fine Grinder with 350 HP and MAC4 Air Classifier, grinding soy flake to soy flour to 200 mesh at the rate of 10,000 lb/hr.

[36] OmniTech International and Four Elements, October 2009. Data Update of Soybean and Soy Feedstocks Production and Life Cycle Assessment of Soy-based Products and Petroleum-based Alternatives. Peer Reviewed Final Report. Prepared for the United Soybean Board. (USB, 2009)

[37] Found at: https://www.solenis.com/en/research-and-development/innovations/soyad-adhesive-technology.

[38] Allen, Anthony, *et al* (Solenis Technologies). March 16, 2015. Soy Based Adhesives with Improved Lower Viscosity. Patent number: US20150086775A1.

[39] Borden, Inc., 12 Feb 1992, Polyamide-epichlorohydrin resin. European Patent Application #91307716.0, Reaction (2) equation.

Table 15 for the datasets used.

Plywood flooring substrate

HempWood flooring uses PureBond® plywood produced by Columbia Forest Products (CFP).[40] PureBond is made of hardwood poplar and, like HempWood lumber, uses the Soyad resin technology instead of traditional formaldehyde and NAF wood resins. Data for plywood is based on the dataset in the U.S. LCI database, with some modifications:

- Electricity use has been changed to RFCW electricity grid, to account for manufacturing in CFP's Craigsville, WV, plant.
- The softwood lumber in the original plywood dataset was replaced by hardwood lumber.
- The phenol formaldehyde resin used in the U.S. LCI database dataset, was replaced by Soyad components (soy flour and PAE, described above). Specifically,[41]
    - Soyad makes up approximately 5% of total mass of PureBond plywood, based on glue application rate calculations, and
    - A ratio of 8.05 of soy flour to PAE (20% solids) was used.

Bonding adhesive and top coat for the flooring

The HempWood plank and plywood are bonded with a polyurethane hot melt adhesive at an application rate of 10 grams/square foot. The final HempWood floor is coated with a diacrylate compound and cured via ultraviolet (UV) light. The coating is applied at a rate of approximately 10 grams/square foot. The diacrylate is modeled as dipropylene glycol diacrylate (DPGDA), a typical UV-cured diacrylate.[42] A dataset on DPGDA was produced with dipropylene glycol and acrylic acid, using stoichiometric calculations.

A2 Transport of Materials to Manufacturing

Materials are transported by heavy duty diesel truck to the Murray, KY, plant. Transportation distances are shown in Table 5 and Table 6.

A3 Manufacturing

Data for HempWood lumber and floor manufacturing are based on 2021 production. The manufacturing data collected cover all processing steps from HempWood lumber production through to production and packaging of the flooring product.

Table 9 HempWood Lumber Energy, Inputs, and Outputs (per 1 kg lumber)

Inputs	Quantity	Unit/kg	Notes
Water	0.079	Gal	removed via drying and evaporates in the air
Soybean oil	0.0004	Gal	
Electricity	0.173	kWh	Tennessee Valley Authority (TVA) grid mix.[43] Per the PCR, electricity is accounted for in A1

[40] https://purebondplywood.com/.

[41] Data on Soyad components and glue application rate from Spayde, Timothy F. et al. (CFP), 2013. US Patent: Cold pressing process for polyamide epichlorohydrin (PAE) based wood adhesive, US 8,470,124 B1, Claim 5. Retrieved from: https://patents.google.com/patent/US8470124B1/en, and confirmed by technical representative at Columbia Forest Products via email communications in May 2022.

[42] Baikerikar, Kiran, et al. (Dow Chemical), paper – retrieved from: https://www.radtech.org/proceedings/2008/papers/083.pdf.

[43] Tennessee Valley Authority (TVA), FY 2021 Sustainability Report, p.27.

Natural gas	341.9	Btu	
Hemp waste used as fuel	0.04	kg	Hemp energy LHV: 17.5 MJ/kg[44]
Diesel	0.00014	gal	
Propane	0.00035	gal	
Outputs			
Solid waste to landfill	0.032	kg	Inert, non hazardous waste to landfill, transported 13 mi.
Recovered material	0.15	kg	Sold

Table 10 HempWood Flooring Energy, Inputs, and Outputs (per 1 ft2 flooring)

Inputs	Quantity	Unit/ft2	Notes
Electricity	0.153	kWh	TVA grid mix. Includes coating and curing. Per the PCR, electricity is accounted for in A1
Outputs			
Recovered waste	0.16	ft^2	Sold as other wood products to make shelving, cabinets, etc.
Solid waste to landfill	0.07	kg	Inert, non hazardous waste to landfill, transported 13 mi.

Final Product Coating

As mentioned above, the flooring is coated using UV curing, a photochemical process in which high-intensity UV light is used to instantly cure or "dry" inks, coatings or adhesives. Data for UV curing comes from a paper that describes the energy usage of this curing process. Specifically, "Samples were run with one pass for pre-cure and two passes for final cure, for a total of 1160mJ/cm2 UVA energy density"[45], amounting to 1.2 MJ/cm^2, or 0.003 kWh/ft2. Since the final HempWood flooring product is not always coated at the Murray facility, this energy has been added to the electricity data in Table 10.

Packaging

HempWood flooring is shipped in 6"x6"x72" recycled cardboard boxes that hold 22 ft2 of floor product. The weight of one box is 1.8 lb, amounting to 0.082 lb/ft2 (0.40 kg/m2) of product. The box is transported 125 mi to Murray, KY, by diesel-powered truck.

CONSTRUCTION STAGE

This stage of the life cycle includes delivery of the floor covering to the place of installation plus production and manufacture of any materials needed for the installation.

A4 Transport to Site

Transport of final, packaged products to customers is done by diesel-powered truck whose data are based on the US LCI database. Since customers in North America vary

[44] Marrot, Laetitia, *et al*. Valorization of Hemp Stalk Waste Through Thermochemical Conversion for Energy and Electrical Applications. **Waste and Biomass Valorization** (2022) 13:2267–2285 https://doi.org/10.1007/s12649-021-01640-6.
[45] Gary Sigel, Ph.D. (Armstrong Flooring), 2017. Floor Coatings with UV LED Curing: A Focus on Performance and Properties.

from year to year and customers may be located in any part of the U.S., the PCR Part B default distance, i.e., 800 km (497 mi),[46] has been assumed.

A5 Installation

According to the manufacturer, HempWood flooring can be installed with nails or glue or tongue and groove on OSB or plywood, or as a floating floor. It must have a vapor barrier. This LCA includes the installation with nails; it does not include the vapor barrier or underlying floor material.

HempWood flooring is installed manually, and the most common installation method, using nails, is modeled for this LCA. Two 18-gauge trim or flooring nails are used per ft2. This amounts to 0.0002 lb/ft2 or 0.0009 kg/m2 galvanized steel.

An estimated 5% of flooring is lost at installation and this loss has been accounted for in the model. The floor product waste is modeled as disposed of in a landfill, which is described in the End-of-Life section. Packaging waste is modeled according to the default packaging waste management provided in PCR Part A, Table 3, specifically: recycling: 68%, incineration: 5%, and landfill: 20%. The amount that is landfilled accounts for biogenic content that is stored and biogenic CO2 that is released. These quantities are presented in the table below:

Table 11 HempWood Flooring Installation

Name	Value	Unit/m2	Notes
Nails	0.0009	Kg	
Flooring product loss per m2	0.51	Kg	
Mass of packaging (corrugated cardboard)	0.4	Kg	
Biogenic carbon in the packaging	0.19	Kg	47% biogenic C content[47]
Total stored biogenic C from the packaging, as CO2	0.076	Kg	Based on landfilling rate of 20%

Transportation distance of the waste materials to their end-of-life fate is based on the PCR Part B default distance, i.e., 161 km (100 mi) by diesel truck.[48]

USE STAGE

The Use stage modules included in the LCA are maintenance and replacement.

B2 Maintenance

For this LCA, cleaning has been modeled using two scenarios: sweeping on a regular basis and vacuuming once per week. These different maintenance scenarios will be presented in the EPD and the results of this report. Use of water on the product is not allowed although swifting with a damp cloth may be done.

[46] PCR Part B, Table 7.
[47] U.S. Environmental Protection Agency Office of Resource Conservation and Recovery, October 2019. Documentation for Greenhouse Gas Emission and Energy Factors Used in the Waste Reduction Model (WARM) Management Practices Chapters. (WARM v.15). Exhibit 6-3: Initial carbon content of corrugated containers.
[48] PCR Part B, Table 7.

Recommended maintenance includes vacuuming wood floors one time per week and/or sweeping every day.[49] With the exception of solid waste, sweeping does not have any additional impacts. The input and output data for vacuuming come from a carpet cleaning and maintenance report prepared by a care and maintenance document by a flooring consortium.[50] Table 12 summarize these data. It should be noted that energy and waste numbers represent an average of the low, medium and high use areas of a commercial building.

Table 12 Maintenance Information

Maintenance Schedule		
Maintenance recommendations: Vacuuming 1x/wk, Sweeping 5x/week		
Vacuuming cycle per product lifetime	1,300	Cycles/RSL
Vacuuming cycle per building service life	3,900	Cycles/ESL
Maintenance Inputs and Outputs	**Quantity per m2/year**	**Quantity per m2/75 yrs (ESL)**
Vacuum	0.21 kWh	15.6 kWh
Sweeping / Solid waste from the vacuum	0.40 kg	29.9 kg

The inputs and outputs, including treatment of solid waste from the vacuum, are included in the model. The electricity use is based on U.S. average grid mix (Table 16).

B4 Replacement

HempWood flooring has an RSL of 25 years. Over the building's ESL of 75 years, the flooring product is replaced two times: at years 25 and 50. In the B4 results, replacement incorporates two additional cycles of production, transport to building, installation, and end-of-life). Replacement of worn parts or a partial floor is not applicable to this product.

END OF LIFE STAGE

End of life includes transportation to location of disposal, plus impacts related to disposal of the waste.

C2 Transport to Disposal

End of life modeling of the wood flooring, plywood underlayment, and other installation materials includes transportation of these materials by heavy-duty diesel-fuel powered truck to a landfill. Transportation distance of the waste materials to their end-of-life fate is based on the PCR Part B default distance, i.e., 161 km (100 mi) by diesel truck.[51]

C4 Disposal of Product

End of life of the HempWood flooring product is modeled as disposed of in a landfill, based on the default product disposal scenario in PCR Part B, Table 2. While the

[49] National Wood Flooring Association (NWFA): https://www.woodfloors.org/maintenance.aspx.
[50] Consortium on Competitiveness for the Apparel, Carpet, and Textile Industries (CCACTI), funded by the State of Georgia, *Care and Maintenance of Commercial Carpet Conventional and Next Generation Technology:* Contents Of Use Phase Gate To Gate; Life Cycle Inventory Summary, Di Lu, M. Overcash and M. Realff, February 2008.
[51] PCR Part B, Table 7.

product may be recycled or reused at EOL, there is currently not enough information on this relatively new product that assures these practices by its users. The data for landfill disposal of wood waste is a DATASMART dataset, derived from an EcoInvent dataset based on average technology in the 2000's. It features a base seal and leachate collection system and contains information on energy, land use, and infrastructure. The dataset has been modified to account for biogenic carbon removals (i.e., sequestration) and emissions due to decay.

Because HempWood flooring is made up of a large percentage of biomass and it is landfilled, it has the potential to sequester carbon indefinitely. Sequestration of carbon has been accounted for in the global warming potential category in this study, based on 1) the quantity of biomass carbon in the flooring, and 2) the long-term storage rate at end-of-life. Sequestered carbon is converted to CO2 and is reported in the C4 end-of-life results.

Table 13 Biobased carbon content of each plant-based component of the flooring

Component	% carbon	Source of Data
Hemp stalks	47%	Marrot (2022)[52]
Soy flour	48%	USB (2009)[53]
Hardwood poplar (in the plywood)	48%	Athena SMI (undated)[54]

The EPA's WARM model[55] calculates impacts from biogenic material in a landfill – specifically the methane (CH4) from decomposition of biomass and CO2 emissions associated with flaring these emissions where landfill gas is not recovered for energy, and CO2 emissions avoided through landfill gas-to-energy projects. The landfilled masses of the HempWood lumber portion and plywood portion of the flooring have been modeled separately, due to (slightly) different biobased materials' carbon contents (Table 13) and WARM v.15 assumptions on products' carbon storage, where wood flooring (HempWood) = 95% stored and medium density fiberboard (accepted proxy for plywood) = 84% stored.[56] Using the C contents in Table 13, the C storage rates, and the landfill models described in WARM v.15 (2019) chapter 6, the following removals and emissions were modeled:

Table 14 Carbon-Related Emissions and Removals

Name	Value	Unit/m2	Notes
Biogenic C removal from flooring product	15.7	Kg CO2	Accounted for in C4 results

[52] Marrot, Laetitia, *et al*. Valorization of Hemp Stalk Waste Through Thermochemical Conversion for Energy and Electrical Applications. **Waste and Biomass Valorization** (2022) 13:2267–2285 https://doi.org/10.1007/s12649-021-01640-6.
[53] USB (2009)
[54] Average value from data for two poplar hardwoods in a C tool developed by Athena Sustainable Materials Institute: Quaking aspen: 47.1% C and Black cottonwood: 49.25% C.
[55] U.S. Environmental Protection Agency Office of Resource Conservation and Recovery, October 2019. Documentation for Greenhouse Gas Emission and Energy Factors Used in the Waste Reduction Model (WARM) Management Practices Chapters. (WARM v.15). Exhibit 6-3: Initial carbon content of corrugated containers.
[56] WARM v.15 Exhibit 6-5.

Biogenic C emission from flooring product	1.82	Kg CO2	Accounted for in C4 results
Biogenic C removal from packaging	0.38	Kg CO2	Accounted for in A5 results
Biogenic C emission from packaging	2.53	Kg CO2	Accounted for in A5 results
Methane emission from flooring product	0.034	Kg CH4	Accounted for in C4 and A5 results, respectively. CH4 generated from landfilled material, that was not captured or converted to CO2
Methane emission from packaging	0.021	Kg CH4	

MATERIALS AND ENERGY

The datasets used are provided in

Table 15.

Table 15 Data Sets Used and Sources of Data

Material	Data Set or Description	Source of data	Publication Date
Hemp cultivation	Ammonium nitrate, as N, at regional storehouse/US- US-EI U	DATASMART	2020
	Ammonium nitrate phosphate, as P2O5, at regional storehouse/US- US-EI U	DATASMART	2020
	Potassium chloride, as K2O, at regional storehouse/US- US-EI U	DATASMART	2020
	Cotton seed, at regional storehouse/US US-EI U	DATASMART	2020
Soy flour	Soy meal, at plant/kg/RNA, plus US average electricity to grind flour	US LCI database	2015
PAE resin	Polyacrylamide {GLO}| market for | APOS, U	Ecoinvent 3.8	2021
	Market for epichlorohydrin GLO	Ecoinvent 3.8	2021
TMPTA	Acrylic acid, at plant/US- US-EI U	DATASMART	2020
Plywood	Plywood, at plywood plant, US SE/kg/US, modified	US LCI database	2015
	Sawn timber, hardwood, planed, air / kiln dried, u=10%, at plant/US- US-EI U	DATASMART	2020
Polyurethane adhesive	Polyurethane, flexible foam, at plant/US-US-EI U	DATASMART	2020
Diacrylate	Dipropylene glycol monomethyl ether, at plant/US- US-EI U	DATASMART	2020
	Acrylic acid, at plant/US- US-EI U	DATASMART	2020
Transport of raw materials	Transport, combination truck, diesel powered/US	USLCI	2015
Transport of waste materials	Transport, single unit truck, diesel powered/US	USLCI	2015
Packaging	Packaging, corrugated board, mixed fibre, single wall, at plant/US- US-EI U	DATASMART	2020
Energy	Natural gas, combusted in industrial boiler/US		2015
	Liquefied petroleum gas, combusted in industrial boiler/US		2015
	Diesel, combusted in industrial equipment/US		2015
Disposal in landfill	Disposal, wood untreated, 20% water, to sanitary landfill/US* US-EI U – modified for HempWood lumber & plywood to apply WARM biogenic factors	DATASMART	2020, modified in 2022

Data for the electricity and energy sources come from the U.S. LCI database.

The electric grid mix for the facility and for U.S. average (during use phase) is presented in the table below. The grid mix data for US average come from U.S. eGRID 2020.[57] The grid mix for TVA comes from its sustainability report.[58]

Table 16 Energy Sources and Grids Used

Grid data and Energy Sources	Tennessee Valley Authority (TVA)	U.S. Average
Coal	16.0%	19.4%
Residual Fuel Oil	0%	0.7%
Natural Gas	28.0%	40.7%
Nuclear	41.0%	19.6%
Hydropower	12.0%	7.1%
Wind	1.5%	8.4%
Photovoltaic	1.5%	2.2%
Other renewable (wood, geothermal…)	0%	1.9%
	100%	**100%**

6. RESULTS

The results are presented two ways. First, per 1 m2 of HempWood flooring in use for the 75-year RSL. Results include production through end of life, plus any product replacements over this period. Second, per requirements of PCR Part B, per 1 m² of the product in one life cycle plus one year of service (called "1 installation"). As mentioned above, results are presented for two maintenance scenarios – with and without vacuuming. The reader is reminded that LCIA results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins or risks.

MAIN RESULTS TABLES

[57] U.S. EPA, 2020. "Emissions & Generation Resource Integrated Database (eGRID), 2018", Washington, D.C., Office of Atmospheric Programs, Clean Air Markets Division. The eGRID is the source of data on the environmental characteristics and sources of the electric power generated in the United States.
[58] Tennessee Valley Authority (TVA), FY 2021 Sustainability Report, p.27.

Table 17 HempWood Flooring LCIA Results – 75 Yrs No Vacuum

75 years - no vacuum		Production	Transport to install	Installation	Maintenance	Replacement	Transport to EOL	EOL	TOTAL
Impact Category	**Unit**	**A1-A3**	**A4**	**A5**	**B2**	**B4**	**C2**	**C4**	
Global warming potential (with biogenic C)	kg CO2-e	11.62	0.87	0.30	0.52	0.88	0.35	-12.70	**1.84**
Acidification potential	kg SO2-e	0.04	0.01	1.94 E-04	4.44 E-03	0.12	2.05 E-03	9.82 E-04	**0.18**
Eutrophication potential	kg N-e	0.01	6.90 E-04	4.29 E-03	7.75 E-04	0.18	3.94 E-04	0.07	**0.27**
Smog creation potential	kg O3-e	0.78	0.29	4.83 E-03	0.12	2.32	0.06	0.03	**3.60**
Ozone depletion potential	kg CFC11-e	3.30 E-07	3.66 E-11	2.50 E-09	2.64 E-07	7.50 E-07	1.71 E-10	4.20 E-08	**1.39 E-06**
Abiotic depletion potential for fossil resources	MJ	93.55	12.41	0.43	16.12	227.31	4.23	3.05	**357.09**

Table 18 HempWood Flooring Other Results Categories – 75 Yrs No Vacuum

75 years - no vacuum		Produc-tion	Transport to install	Install-ation	Mainten-ance	Replace-ment	Transport to EOL	EOL	TOTAL
Category	Unit	A1-A3	A4	A5	B2	B4	C2	C4	
Resource Use: Energy									
Non-renewable primary energy used as an energy carrier (fuel)	MJ (LHV)	122.38	13.18	0.47	17.38	287.82	4.49	3.39	**449.10**
Non-renewable primary energy resources used as raw materials	MJ (LHV)	0	0	0	0	0	0	0	**0**
Renewable primary energy used as an energy carrier (fuel)	MJ (LHV)	52.21	0	2.53 E-03	0.33	104.48	1.02 E-04	0.03	**157.05**
Renewable primary energy resources used as raw materials	MJ (LHV)	177.60	0	0	0	355.20	0	0	**532.81**
Resource use: Materials									
Use of secondary materials	Kg	0	0	0	0	0	0	0	**0**
Use of renewable secondary fuels	MJ (LHV)	0	0	0	0	0	0	0	**0**
Use of non-renewable secondary fuels	MJ (LHV)	0	0	0	0	0	0	0	**0**
Use of recovered energy	MJ (LHV)	0	0	0	0	0	0	0	
Use of net fresh water (inputs minus outputs)	m3	0.12	0	1.89 E-04	0.02	0.24	1.07 E-05	2.84 E-03	**0.38**
Waste categories									
Non-hazardous waste disposed	Kg	0.93	0	0.61	119.30	24.62	0.51	10.25	**156.23**
Hazardous waste disposed	Kg	0	0	0	0	0	0	0	**0**
Radioactive waste disposed	Kg	0	0	0	0	0	0	0	**0**
Other output flows									
Components for reuse	Kg	0	0	0	0	0	0	0	**0**
Materials for recycling	Kg	2.48	0	0	0	4.96	0	0	**7.43**
Materials for energy recovery	Kg	0	0	0	0	0	0	0	**0**
Exported energy	MJ (LHV)	0	0	0	0	0	0	0	**0**

Table 19 HempWood Flooring LCIA Results – 1 Installation No Vacuum

1 installation, 1 year - no vacuum		Produc-tion A1-A3	Transport to install A4	Install-ation A5	Mainten-ance B2	Transport to EOL C2	EOL C4	TOTAL
Impact Category	**Unit**							
Global warming potential (with biogenic C)	kg CO2-e	11.62	0.87	0.30	0.01	0.35	-12.70	**0.45**
Acidification potential	kg SO2-e	0.04	0.01	1.94 E-04	5.92 E-05	2.05 E-03	9.82 E-04	**0.06**
Eutrophication potential	kg N-e	0.01	6.90 E-04	4.29 E-03	1.03 E-05	3.94 E-04	0.07	**0.09**
Smog creation potential	kg O3-e	0.78	0.29	4.83 E-03	1.58 E-03	0.06	0.03	**1.16**
Ozone depletion potential	kg CFC11-e	3.30 E-07	3.66 E-11	2.50 E-09	3.52 E-09	1.71 E-10	4.20 E-08	**3.78 E-07**
Abiotic depletion potential for fossil resources	MJ	93.55	12.41	0.43	0.21	4.23	3.05	**113.87**

Table 20 HempWood Flooring Other Results Categories – 1 Installation No Vacuum

1 installation, 1 year - no vacuum		Produc-tion	Transport to install	Install-ation	Mainten-ance	Transport to EOL	EOL	TOTAL
Category	Unit	A1-A3	A4	A5	B2	C2	C4	
Resource Use: Energy								
Non-renewable primary energy used as an energy carrier (fuel)	MJ (LHV)	122.38	13.18	0.47	0.23	4.49	3.39	**144.14**
Non-renewable primary energy resources used as raw materials	MJ (LHV)	0	0	0	0	0	0	**0**
Renewable primary energy used as an energy carrier (fuel)	MJ (LHV)	52.21	0	2.53 E-03	0.00	1.02 E-04	0.03	**52.24**
Renewable primary energy resources used as raw materials	MJ (LHV)	177.60	0	0	0	0	0	**177.60**
Resource use: Materials								
Use of secondary materials	Kg	0	0	0	0	0	0	**0**
Use of renewable secondary fuels	MJ (LHV)	0	0	0	0	0	0	**0**
Use of non-renewable secondary fuels	MJ (LHV)	0	0	0	0	0	0	**0**
Use of recovered energy	MJ (LHV)	0	0	0	0	0	0	
Use of net fresh water (inputs minus outputs)	m3	0.12	0	1.89 E-04	2.52 E-04	1.07 E-05	2.84 E-03	**0.12**
Waste categories								
Non-hazardous waste disposed	Kg	0.93	0	0.61	1.59	0.51	10.25	**13.90**
Hazardous waste disposed	Kg	0	0	0	0	0	0	**0**
Radioactive waste disposed	Kg	0	0	0	0	0	0	**0**
Other output flows								
Components for reuse	Kg	0	0	0	0	0	0	**0**
Materials for recycling	Kg	2.48	0	0	0	0	0	**2.48**
Materials for energy recovery	Kg	0	0	0	0	0	0	**0**
Exported energy	MJ (LHV)	0	0	0	0	0	0	**0**

Table 21 HempWood Flooring LCIA Results – 75 Yrs With Vacuum

75 years - with vacuuming		Produc-tion	Transport to install	Install-ation	Mainten-ance	Replace-ment	Transport to EOL	EOL	TOTAL
Impact Category	**Unit**	**A1-A3**	**A4**	**A5**	**B2**	**B4**	**C2**	**C4**	
Global warming potential (with biogenic C)	kg CO2-e	11.62	0.87	0.30	39.44	0.88	0.35	-12.70	**40.77**
Acidification potential	kg SO2-e	0.04	0.01	1.94 E-04	0.17	0.12	2.05 E-03	9.82 E-04	**0.35**
Eutrophication potential	kg N-e	0.01	6.90 E-04	4.29 E-03	0.01	0.18	3.94 E-04	0.07	**0.28**
Smog creation potential	kg O3-e	0.78	0.29	4.83 E-03	1.98	2.32	0.06	0.03	**5.47**
Ozone depletion potential	kg CFC11-e	3.30 E-07	3.66 E-11	2.50 E-09	1.25 E-06	7.50 E-07	1.71 E-10	4.20 E-08	**2.37 E-06**
Abiotic depletion potential for fossil resources	MJ	93.55	12.41	0.43	511.73	227.31	4.23	3.05	**852.70**

Table 22 HempWood Flooring Other Results Categories – 75 Yrs With Vacuum

75 years - with vacuuming		Produc-tion	Transport to install	Install-ation	Mainten-ance	Replace-ment	Transport to EOL	EOL	TOTAL
Category	Unit	A1-A3	A4	A5	B2	B4	C2	C4	
Resource Use: Energy									
Non-renewable primary energy used as an energy carrier (fuel)	MJ (LHV)	122.38	13.18	0.47	762.33	287.82	4.49	3.39	**1194.05**
Non-renewable primary energy resources used as raw materials	MJ (LHV)	0	0	0	0	0	0	0	**0**
Renewable primary energy used as an energy carrier (fuel)	MJ (LHV)	52.21	0	2.53 E-03	40.92	104.48	1.02 E-04	0.03	**197.64**
Renewable primary energy resources used as raw materials	MJ (LHV)	177.60	0	0	0	355.20	0	0	**532.81**
Resource use: Materials									
Use of secondary materials	Kg	0	0	0	0	0	0	0	**0**
Use of renewable secondary fuels	MJ (LHV)	0	0	0	0	0	0	0	**0**
Use of non-renewable secondary fuels	MJ (LHV)	0	0	0	0	0	0	0	**0**
Use of recovered energy	MJ (LHV)	0	0	0	0	0	0	0	**0**
Use of net fresh water (inputs minus outputs)	m3	0.12	0	1.89 E-04	0.07	0.24	1.07 E-05	2.84 E-03	**0.43**
Waste categories									
Non-hazardous waste disposed	Kg	0.93	0	0.61	119.30	24.62	0.51	10.25	**156.23**
Hazardous waste disposed	Kg	0	0	0	0	0	0	0	**0**
Radioactive waste disposed	Kg	0	0	0	0	0	0	0	**0**
Other output flows									
Components for reuse	Kg	0	0	0	0	0	0	0	**0**
Materials for recycling	Kg	2.48	0	0	0	4.96	0	0	**7.43**
Materials for energy recovery	Kg	0	0	0	0	0	0	0	**0**
Exported energy	MJ (LHV)	0	0	0	0	0	0	0	**0**

Table 23 HempWood Flooring LCIA Results – 1 Installation With Vacuum

1 installation, 1 year - with vacuuming		Produc-tion	Transport to install	Install-ation	Mainten-ance	Transport to EOL	EOL	TOTAL
Impact Category	**Unit**	**A1-A3**	**A4**	**A5**	**B2**	**C2**	**C4**	
Global warming potential (with biogenic C)	kg CO2-e	11.62	0.87	0.30	0.53	0.35	-12.70	**0.97**
Acidification potential	kg SO2-e	0.04	0.01	1.94 E-04	2.25 E-03	2.05 E-03	9.82 E-04	**0.06**
Eutrophication potential	kg N-e	0.01	6.90 E-04	4.29 E-03	1.78 E-04	3.94 E-04	0.07	**0.09**
Smog creation potential	kg O3-e	0.78	0.29	4.83 E-03	0.03	0.06	0.03	**1.19**
Ozone depletion potential	kg CFC11-e	3.30 E-07	3.66 E-11	2.50 E-09	1.66 E-08	1.71 E-10	4.20 E-08	**3.91 E-07**
Abiotic depletion potential for fossil resources	MJ	93.55	12.41	0.43	6.82	4.23	3.05	**120.48**

Table 24 HempWood Flooring Other Categories Results – 1 Installation With Vacuum

1 installation, 1 year - with vacuuming		Produc-tion	Transport to install	Install-ation	Mainten-ance	Transport to EOL	EOL	TOTAL
Category	**Unit**	**A1-A3**	**A4**	**A5**	**B2**	**C2**	**C4**	
Resource Use: Energy								
Non-renewable primary energy used as an energy carrier (fuel)	MJ (LHV)	122.38	13.18	0.47	10.16	4.49	3.39	**154.07**
Non-renewable primary energy resources used as raw materials	MJ (LHV)	0	0	0	0	0	0	**0**
Renewable primary energy used as an energy carrier (fuel)	MJ (LHV)	52.21	0	2.53 E-03	0.55	1.02 E-04	0.03	**52.79**
Renewable primary energy resources used as raw materials	MJ (LHV)	177.60	0	0	0	0	0	**177.60**
Resource use: Materials								
Use of secondary materials	Kg	0	0	0	0	0	0	**0**
Use of renewable secondary fuels	MJ (LHV)	0	0	0	0	0	0	**0**
Use of non-renewable secondary fuels	MJ (LHV)	0	0	0	0	0	0	**0**
Use of recovered energy	MJ (LHV)	0	0	0	0	0	0	**0**
Use of net fresh water (inputs minus outputs)	m3	0.12	0	1.89 E-04	9.12 E-04	1.07 E-05	2.84 E-03	**0.12**
Waste categories								
Non-hazardous waste disposed	Kg	0.93	0	0.61	1.59	0.51	10.25	**13.90**
Hazardous waste disposed	Kg	0	0	0	0	0	0	**0**
Radioactive waste disposed	Kg	0	0	0	0	0	0	**0**
Other output flows								
Components for reuse	Kg	0	0	0	0	0	0	**0**
Materials for recycling	Kg	2.48	0	0	0	0	0	**2.48**
Materials for energy recovery	Kg	0	0	0	0	0	0	**0**
Exported energy	MJ (LHV)	0	0	0	0	0	0	**0**

ADDITIONAL RESULTS INTERPRETATION

The figures below present the life cycle stages for the global warming potential category, highlighting the effect of the removal of biomass carbon.

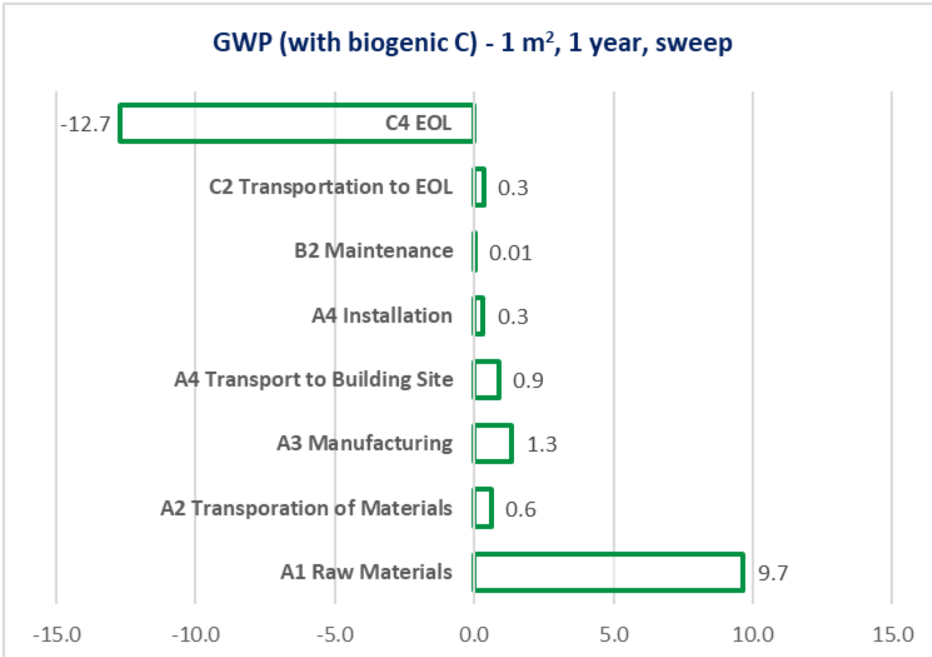


Figure 2 Breakdown of Life Cycle Stages for GWP – No Vacuum

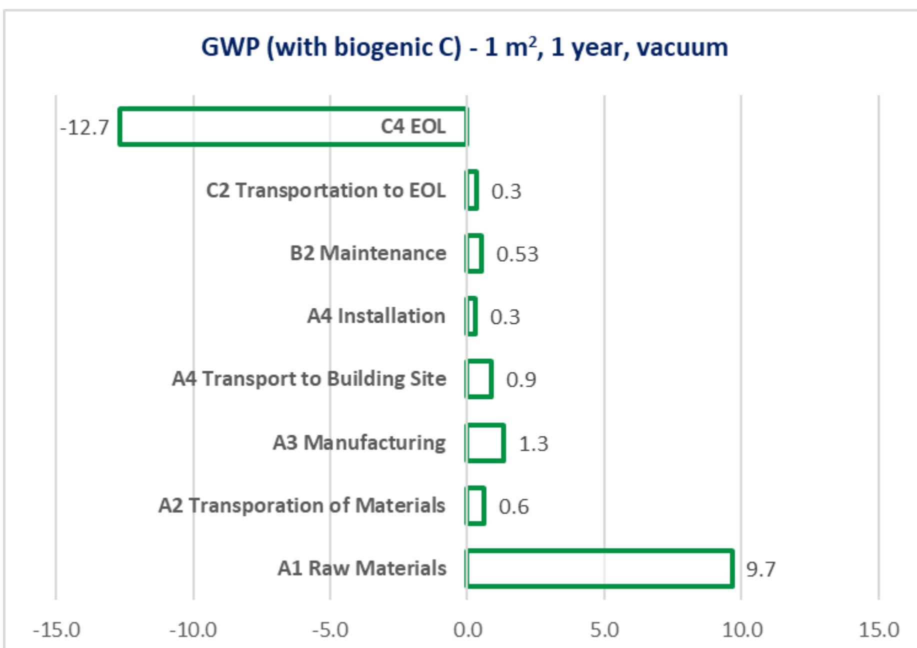


Figure 3 Breakdown of Life Cycle Stages for GWP – With Vacuum

Raw materials production is further broken down as follows.

Table 25 HempWood Flooring A1 Raw Materials Production

Impact Category	Unit	Total	Plywood	Hempwood lumber	Dipropylene glycol diacrylate UV coating	Hot melt adhesive binder	Electricity (at manuf-acturing)
Global warming potential (with biogenic C)	kg CO2-e	9.67	6.40	1.12	0.49	0.58	1.08
Acidification potential	kg SO2-e	0.03	0.02	0.01	1.57E-03	2.29E-03	4.51E-03
Eutrophication potential	kg N-e	0.01	2.26E-03	1.31E-03	1.46E-03	1.09E-03	3.72E-04
Smog creation potential	kg O3-e	0.52	0.31	0.12	0.02	0.03	0.04
Ozone depletion potential	kg CFC11-e	2.92E-07	1.37E-08	7.37E-08	1.22E-07	3.04E-09	7.97E-08

Because the sequestration of carbon in the product causes an offset in the GWP results, the end-of-life (C4) is broken down into the sequestered carbon and the landfill emissions related to landfill management and biomass in the landfill. See C4 discussion on page 20.

Table 26 HempWood Flooring C4 EOL Global Warming Potential

Impact Category	Unit	Total	Sequestered C (as carbon dioxide)	Disposal of Hempwood	Disposal of Plywood
Global warming potential (with biogenic C)	kg CO2-e	-12.70	-15.71	1.18	1.83

Note that these two latter tables will not be included in the EPD, unless desired by the end-client.

7. Data Quality Requirements and Evaluation

Overview

This LCA adheres to the ISO standards on data quality to help ensure consistency, reliability, and clear-cut evaluation of the results. The following aspects of the study's data quality are described in accordance with ISO 14044:

- Representativeness of the data in the study, which includes an assessment of the temporal, geographical, and technological coverage of the model;
- Consistency – the qualitative assessment of how uniformly the study methodology is applied to the various components of the analysis;
- Reproducibility – the qualitative assessment of the extent to which information about the methodology and data values allows an independent practitioner to reproduce the results reported in the study;
- Precision – the measure of the variability of the data values for each data category expressed;
- Completeness – the percentage of flow that is measured or estimated;
- Uncertainty of information.

DATA QUALITY AS APPLIED TO THIS STUDY

Temporal, Geographical, and Technological Representativeness
In general, the best data available at the time of the study were used. The background LCA data, i.e., the data linked together in the model, datasets came mainly from DATASMART which is NA customized, and the U.S. LCI database. In the case where there were no data on a particular material, data sets were built or taken from published LCA studies. Proxy data were used where appropriate, to avoid a complete exclusion of that material in the inventory. In all cases, appropriateness of use of each material was ascertained to maintain the highest level of data quality.

Temporal
Temporal representativeness describes the age of data and the minimum length of time over which data are collected. PCR Part A requires data sets used for calculations to be current within ten (10) years for generic data and within the five (5) years for producer-specific data. The data applied to this study represent the current HempWood flooring product and current Fibonacci manufacturing practices. Product components and facility energy use are current. Energy and transportation data are based on the mid-2010's, and production data for materials are based on 2010's and mid- to high-2000's data sets. It should be noted that all background data of the materials (esp. energy and transport) are updated whenever new database versions are released. Temporal representation data quality score is between a 2 and 3, using the ecoinvent v.3's data quality pedigree matrix.[59] The table below presents more detail on the age of the data.

Geographical
Geographical representativeness describes the geographical area from which data for unit processes are collected to satisfy the goal of the study. Data for energy and transportation are NA-based. Data for materials and processes are based on a combination of NA and European sources; U.S. LCI is NA-based. DATASMART started out as Europe-based with NA customization and it has begun to include NA-based processes. EcoInvent has some NA-based data but is mostly European-based. Geographical correlation data quality score is between a 2 and 3, using the ecoinvent v.3's data quality pedigree matrix.

Technological
Technological coverage, corresponding to the time period of the data sets, is current. Technological coverage for the Murray, KY, is current, and technological coverage for the materials and processes in the floor product are in most cases industry average, and in some instances, typical. The technological data representation is between 1 and 2 using ecoinvent's matrix.

The table below provides more detail on the data.

[59] Ecoinvent Centre, 2013. ecoinvent - report No. 1 **(v3)** Overview and methodology - Data quality guideline for the ecoinvent database version 3. Table 10.4 "Pedigree matrix used to assess the quality of data sources".

Table 27 Temporal, Technological, and Geographical coverage

Process	Temporal Information	Technological coverage	Type of data	Geographical coverage	Source of data
Data sets for materials in each product	Data sets range from high 2000s through the 2010's.	For generic materials, the most representative technology is used. Most data sets represent average or typical technologies.	Primary for some; publicly-available/ secondary for most	North American and European data	U.S. LCI Database, DATASMART, ecoinvent. See Table 15.
Transport of BOMs	2021 sourcing locations	n/a	Transport distances calculated	Sourcing data for Fibonacci plant	Facility questionnaire
Transportation data sets	2010's data	Average technologies	Publicly-available	North American data	U.S. LCI Database
Manufacturing	2021	Fibonacci technology	Measured and calculated; compiled from utility document by Fibonacci	Fibonacci Murray, KY, plant	Facility questionnaire
Energy and fuel data sets	2010s. Electricity grid mixes are from EPA eGrid 2020	The most representative technologies	Publicly-available	North American data	U.S. LCI Database
Product final packaging	Current packaging methods	n/a	Measured and calculated	Packaging for Fibonacci product	Facility questionnaire
Distribution to customers	n/a – PCR default distance.	n/a	Publicly-available data sets	NA customer data	PCR
Use phase	Study published in mid-late 2000s for current cleaning and maintenance	Typical vacuum cleaner data	Publicly-available	North American data	Carpet & Rug Institute
EOL	n/a – PCR default EOL practice.	Landfill technologies are average across NA	Publicly-available	NA data	PCR

Consistency
Consistency is a qualitative understanding of how uniformly the study methodology is applied to the various components of the study. The LCA is consistent with the ISO standards and with the requirements of the PCRs. The modeling is consistent with LCAs and EPDs of other flooring products and wood floor products.

Reproducibility
The level of detail and transparency provided in this report allow the results of this study to be reproduced by another LCA practitioner.

Precision and Completeness
Precision represents the degree of variability of the data values for each data category. Precision cannot be quantified for this study since only one set of data was provided. Facility data are precise, as the facility focuses on HempWood lumber and flooring. Completeness is the percentage of flows that have been measured or estimated. The data have a score of 1 using ecoinvent's matrix.

8. Limitations and Uncertainty

It should be borne in mind that LCA, like any other scientific or quantitative study, has limitations and is a far from perfect tool for assessing the environmental impacts and attributes associated with product systems. Much of the data used for modeling the materials is secondary. Because the quality of secondary data is not as good as primary data, the use of secondary data becomes an inherent yet accepted limitation to the study: they cover a broad range of technologies, time periods, and geographical locations. However, from a practical standpoint it is impossible to collect actual process data for each of the hundreds or thousands of unit processes included in a complete life cycle model so the use of secondary data in an LCI is normal and necessary.

Nevertheless, the use of secondary data does present some uncertainty and therefore some margin of error. Because hundreds of data sets are linked together and because it is often unknown how much the data used deviate from the specific system being studied, quantifying data uncertainty for the complete system becomes very challenging. As a result, it is not possible to provide a reliable quantified assessment of overall data uncertainty for the study.

Should claims or assertions be made on the environmental performance of the product, the public should be informed of these inherent limitations.

9. Conclusions

The goal of this study was to perform an LCA on HempWood flooring, that represents the operations at Fibonacci's Murray, KY, plant, which can be used to produce an EPD. The LCA was performed in accordance with the ISO standards on LCA as well as other standards and the applicable and appropriate PCRs for flooring products. Total cradle-to-grave results plus life cycle stage contribution analyses were presented for the HempWood flooring product, and these results should be appropriate for use in the EPD.

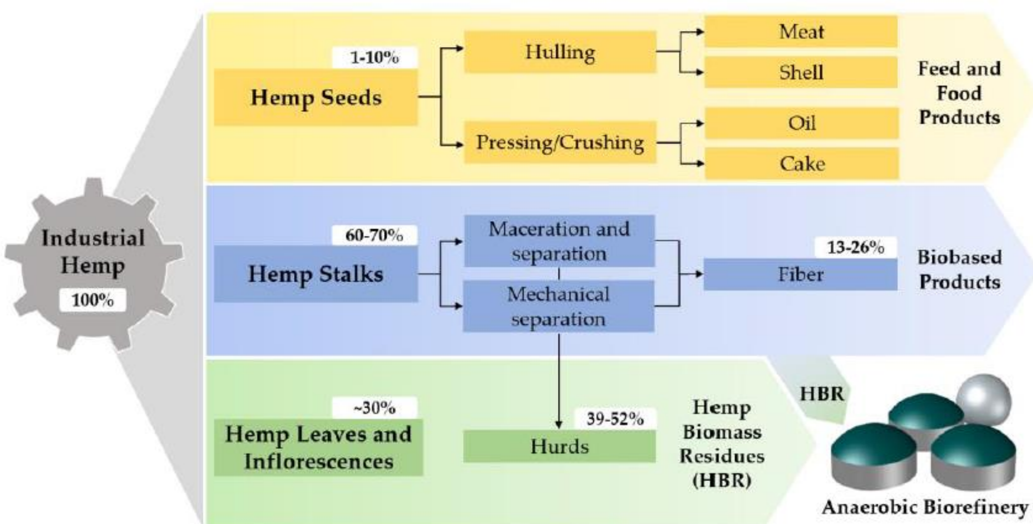
10. APPENDIX A HEMP PRODUCTS AND PRICE

Due to the high variability of hemp yields and its different applications, and an evolving and growing market, this study used the yields of grain and stalk and the purchase price of the crops purchased by Fibonacci, so that it is specific to HempWood (see Table 8). Additional information follows below.

Hemp Crop and Products Yield

The per acre yield of hemp plants varies greatly. University of Wisconsin-Madison's Wisconsin Hemp Division of Extension says the following: "Yields can vary widely depending on the variety, local climatic conditions, cultivation method, and grower experience. For grain, new growers have reported yields between 250-700 lbs/acre. More experienced growers can expect between 800- 1,800+ lbs/acre. For fiber, the average yield for dual purpose crops (those varieties which are harvested for grain and fiber) is 0.75-2 tons/acre. For hemp produced solely for fiber, the average yield is between 3-5 tons per acre."[60]

Additionally, due to the many varieties of hemp, the yield of each useful/marketable coproduct may vary greatly. Below is a diagram showing how variable hemp coproducts can be.[61]



Price

Price of fiber/stalk. Indeed, there are published prices in USDA, and we evaluated these, including the prices that Fibonacci pays, before doing the economic allocation. The USDA prices are for fiber, either retted ($0.93/lb) or "all" ($1.50/lb). [62] Notably, the price listed in the USDA report is not the same "product" as what Fibonacci buys; they are for retted fiber or fiber already extracted from the stalk while HempWood utilizes the full unprocessed, non-retted/dried stalk.

[60] https://fyi.extension.wisc.edu/hemp/industrial-hemp-agronomics/.

[61] Taken from: Energies 2020, 13, 3361; doi:10.3390/en13133361.

[62] USDA, National Agricultural Statistics Service, National Hemp Report (February 2022), Table, page 19 entitled, "Industrial Hemp by Type Yield, Median Yield, Price, and Median Price - United States: 2021".

Other research on unprocessed stalk is along the lines of Fibonacci's average price/lb of $0.075 (Table 8). An article about growing hemp addresses the economic viability of producing hemp for fiber: "Despite the yield variation, hemp for fiber must pencil out to be economically viable. 'Payment ranges from 7-11 cents per pound, or sometimes a minimum guarantee per acre, whichever is larger'",[63] says Steve Rutledge, who oversees operations of corn, forage crops, hemp, soybeans and wheat outside of Louisville, KY. In another article, Fibershed, a non-profit organization who "develops regional fiber systems that build ecosystem and community health", said this in 2020 about hemp fiber stalk: "The best offer that we received for industrial hemp stalk this year was $0.08/lb.[64]

Price of grain. The study uses Fibonacci's stated prices for the dual crop, which are representative of both the region and the actual purchased product that this LCA covers. The USDA average price is ($1.51/lb) but that may not be representative of Kentucky.[65]

A potential shift in prices within several years. We acknowledge that published data for hemp grain and fiber (or stalk) prices could be defensible for this EPD work. For fiber, we explain why the USDA numbers are not representative for the hemp in HempWood (i.e., full stalks). For grain, we opted to use the actual pricing of the crop purchased by Fibonacci, choosing the more representative value. As the industrial hemp market is fairly young in the U.S., – the 2018 Farm Bill allowed industrial hemp to be grown in the U.S. – we expect that the market for hemp coproducts will evolve. For example, there are currently restrictions on the use of hemp meal for animal feed, etc. [66] Once some of those restrictions are lifted over the next few years, potentially more stable prices and production volumes will yield more reliable and complete data collected for the USDA report, in all the categories reported. On the other hand, it will be interesting to see how hemp grain for animal feed might compete with other feed grains once the restrictions are lifted. We will definitely revisit this issue during the update of the HempWood EPD in 5 years.

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[63] Bennet, C., 2019. Growing Hemp for CBD, Seed or Fiber. Found at: https://www.agweb.com/news/crops/crop-production/growing-hemp-cbd-seed-or-fiber-0.

[64] Fibershed website. Found at: https://fibershed.org/2020/09/16/harvesting-hemp-reflecting-on-opportunities-with-the-one-acre-exchange/.

[65] USDA (2022), table on p. 19. Data for Region 6 (includes Kentucky) is not specified (see USDA (2022) p.9 and p.11).

[66] See, for example, Hemp Benchmark, November 2020. Introduction to the U.S. Grain Hemp Market. Found at: https://www.hempbenchmarks.com/hemp-market-insider/introduction-to-grain-hemp/.