Environmental Impacts of Bio-Based Vapor Control Layers in Wood Structures

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Abstract

Despite exemplary performance and longevity, vapor control products for wall assemblies such as housewraps and tar felts remain highly dependant upon non-renewable and soon-to-be depleted oil reserves. In this paper, Fast Track Life Cycle Analyses (LCA) are performed on bio-based alternatives to these products by using eco-costs as indicator for comparison between the following options: ethylene membranes, natural pitch paper, straw-bale construction, hempcrete, and expanded agglomerated cork. It is concluded that the agricultural production of bio-based construction materials remains unsustainable and therefore may, on a case-by-case basis, mitigate the advantages of biodegradable materials. Further, while ethylene membranes represent the option of least impact, assemblies where the vapor control layer may also act as thermal insulation could hypothetically offset the wall's total environmental burden. Similarly, using agricultural waste material can further reduce the total eco-costs of other bio-based solutions beyond that of polyethylene membranes.

Keywords

Life Cycle Analyses (LCA), bio-based materials, vapor control layer, eco-costs, permeance.

1. Introduction

At the moment Cradle to Cradle (C2C) was first published in 2002, few could have known how much the hopes placed in sustainable development would, 15 years later, yield such a drastic transformation of our building technology. Sustainable development, as understood by C2C authors Braungart and McDonough, should consider the capacity of our systems to perpetuate our environment and themselves indefinitely. As the current efforts in sustainable architecture demonstrate, it is now possible to construct carbon negative housing and offices. Every effort made to reduce the carbon footprint of our homes helps to push back climate change ever so slightly. Yet, low energy consumption cannot necessarily be associated with renewability. Despite a stellar energy performance, even housing of the highest distinctions (whether BREEAM or LEED) still depends on non-renewable products and raw substances at a structural level. With a significant reliance on crude oil derivates, the products forming the weatherproofing layer of our homes are particularly problematic to replace. As a matter of fact, the non-profit Cradle to Cradle Products Innovation Institute, which certifies innovative construction products for this stated issue, offers no alternative for vapor control layers (VCL) specifically. As crude oil supplies are predicted to dwindle by the midcentury, the manufacturing of these crucial products may be discontinued consequently with the lack of raw material or the unmarketable prices of a post-oil society. The search for viable replacements to oil-based VCL is one of necessity.

Moreover, the task is further complicated by the overbearing importance of weatherproofing products on the home as a wholistic system. Whether the weatherproofing's failure is caused by faulty design or premature degradation is irrelevant; the consequences can nevertheless be devastating for the homeowners' health and finances. The World Health Organization reports that at least 20% of dwellings in 14 European countries, the United States, and Canada, presented one or more signs of dampness in a 2009 publication (WHO, 2009). There is no understating the fact that lives can be broken as result of minor water infiltration issues, particularly where costs often befall a single family. Nevertheless, this severe outlook on the role of weatherproofing echoes both the difficulty and the necessity of developing truly sustainable weatherproofing alternatives. An early investigation of this matter can only benefit the prospect of long-term, decades-spanning empirical testing of these new construction methods in the field, and further reduce the risk of malfunction.

This paper's objective is to analyse and contrast the most prominent and low-risk alternatives to the current non-renewable VCLs for a temperate maritime climate of northern Europe by using the Fast Track Life Cycle Analysis method. As per the limited length of this format, the analysis will be restricted to above-grade exterior wall VCLs only and will thus be exempt of the special requirements for basements in the analysis. First, the methodological parameters are detailed as to provide clear boundaries for the LCA. A limited list of the most promising alternatives from 3 distinct fields of investigation will be established: contemporary methods, historical or vernacular alternatives, and emerging materials. The Life Cycle Analysis of these products as well as contemporary research will provide most of the information used to formulate the conclusion.

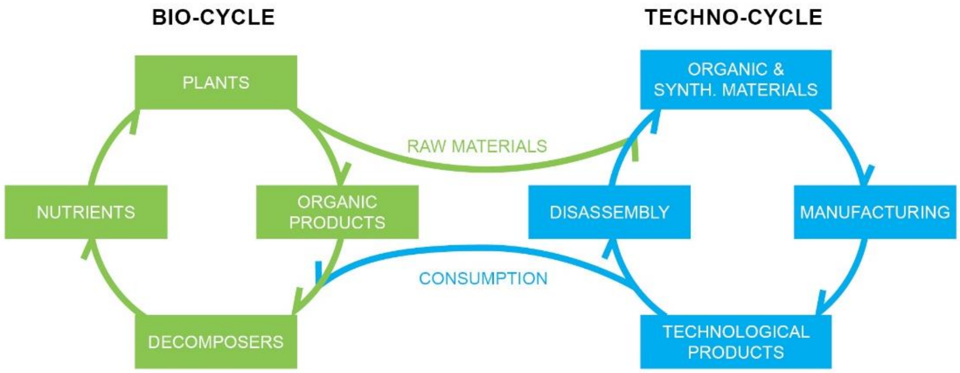
2. Selection Criteria for Vapor Control Layers

The task of evaluating past and present waterproofing methods begins with establishing the search parameters, namely: the sustainability criteria, the ideal water resistance performance, and the search pattern.

2.1. Definition of Sustainability

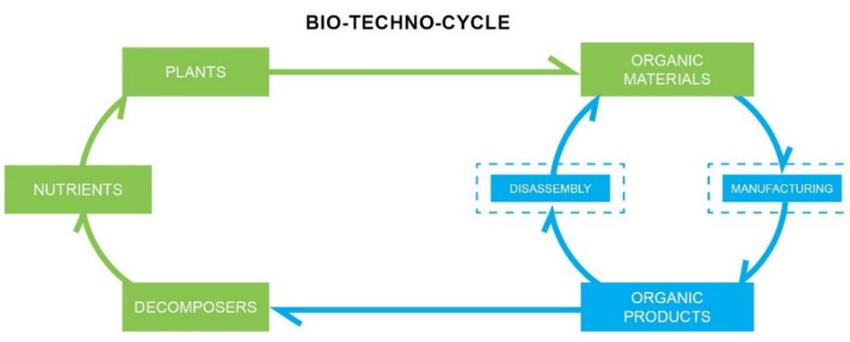
As it was explained in the opening, the current VCL options for any construction project are limited to products derived from the petrochemical industry. While some of these products do achieve a small carbon footprint, their non-renewable raw materials will seriously limit their viability in the upcoming decades. It is also of great concern that these products present a health hazard towards occupants and environment alike, whether in the form of toxic particle emissions or landfill debris. For clarity, the Cradle to Cradle definition of sustainability has been adopted for this paper and will be referenced throughout the analysis. The core principles of this definition are summarized in the following diagram:

Figure 1. Material Flow Within a Cradle-to-Cradle Paradigm, reproduced from diagrams of William McDonough presented at TED 2005 (McDonough, 2005)



In this idealized arrangement, all technological products and components of a system are either disassembled and given a second life, or they are returned to nature to become part of the natural cycle again. Construction waste is better imagined as "technological nutrient" as it can be broken down to its raw materials and reused for production (McDonough, 2005). In doing so, the cradle-to-cradle renders the techno-cycle truly circular (as shown) and economical value is created from waste while reducing the total mass of pollutant sent to the landfill. This specific definition was selected for its various pragmatic advantages. It withstood the test of time and now stands among the most recognized and employed definition, and is thus easier to grasp by a general public and non-specialized architects. It also serves as a proven standard for an internationally recognized certification of construction materials (referenced in the introduction), which by extension includes waterproofing products. Additionally, the Cradle to Cradle principles and terminology are compatible with Eco-Cost calculations, the latter being a "single indicator" for Life-Cycle Analyses (LCA). Most importantly, the use of eco-costs allows for a rapid, yet "robust (…) cradle-to-cradle calculations in LCA for products and services in the theory of the circular economy" (TU Delft, 2017)

Figure 2. Material Flow Within a Fully Biodegradable Construction System, personal image.



However, the techno-cycle is not as efficient at recycling as the biological cycle of organic materials; the loss of precious substances and the high levels of energy required to dismantle and refine the waste into usable raw materials remain a form of lesser ecological burden. But, transitioning towards fully organic and biodegradable construction materials may diminish this impact further, if not completely. In a purely bio-based architecture, waste may be returned to the land *ad infinitum*, thus initializing the germination of the next generation of harvested materials. Both biological and technological cycles become united into a single circle.

2.2. Permeability Requirements

The search parameters must also take into account the performance expected from the alternative solutions proposed in this paper. As multiple sources of expertise have confirmed, weatherproofing a home with either an air or vapour barrier is not a simple quest for the lowest degree of permeance. In temperate climates like the Netherlands, an ideal VCL should provide sufficient permeance to allow some vapor transfer at specific times of the year (Allen et al., 2017; Lstiburek, 2004). The displacement of gaseous water through the wall assembly is necessary to insure that the structure can evacuate excess humidity during hot days and keep water out under normal circumstances (Holladay, 2000). It bears repeating that, for this paper, the climatic zone selected for reference is that of the Netherlands, specifically a "temperate maritime climate". As such, the proper recommendations for a climate mixing hot and cold must be observed. Appropriate moisture control in an exterior wall in those specified conditions can be achieved using two distinct methods (Lstiburek, 2004), one of which can be rejected. The first option allows a home to be built as if the climate was either cold *or* hot, but be complemented by added interior moisture control in the form of dehumidifiers, air exchangers or other form of mechanical component. Alternatively, the second option is to rely on a *flow-through* vapor retarder that prevents water accumulation. As the objective of this paper is to evaluate weatherproofing materials on their own merit, the first option can be rejected on the grounds of *adding* mechanical apparatus that would otherwise not be needed. While in practice the first option can always be justified under the right circumstances, the heavy reliance on virgin metal and oil derivates of these systems collides with the ultimate goal of finding strictly renewable alternatives. For these reasons, only option 2 is retained. More specifically, it also assumes that the vapour retardant is located inside the exterior wall assembly and not facing the interior. This implies that no impermeable or semi-permeable finishing may be used; the use of certain latex paints on the interior face of the wall is ill-advised (Holladay, 2000). Simply put, a double layer of vapor retarders would "not allow the wall assembly to dry towards the interior during cooling periods" (Lstiburek, 2004). As such, the ideal rating for a vapor retarder in the specified temperate conditions corresponds to Class I and II, impermeable and semi-impermeable, corresponding respectively to less than 0.1 perm and between 0.1 and 1 U.S perm units.

2.3. Selection Criteria

A limited number of bio-based vapor control layers (VCL) had to be selected for the sake of brevity. Three categories of solutions were distinguished in an effort to include options from varying origins and workings. First, the current dominating products on the market are analysed as their popularity insures that their production and performances are well regulated. It may also reveal the causes of their popularity and further inform the desirable characteristics of an adequate VCL. Second, VCLs that originate from vernacular architecture are considered as they are both "time-tested" and "locally sourced" by historical necessity. However, this category also raises the most problems regarding the acceptability of these methods in regards to code compliance and resident comfort as they are complex to integrate with the modern expectations of serviceability. The third category integrates new innovative products that are either under development or having recently entered the construction market. Their main cause for problems concerns the long-term testability of their claims. In total, six (including stucco) distinct Fast -track LCA are conducted for this report, although more options have been explored, some fully calculated, but nevertheless rejected due to the lack of credible data. For instance, an entire section concerning animal based products and such as beeswax caulking, waxed cotton, and “hard fats” had to be abandoned because neither the permeance nor the nominal thickness of these products could be identified in the current scientific literature. Similarly, options like seaweed insulation, sailcloth, and pine resin were eliminated for the same reason in addition to there being no corresponding Eco-Costs entries in the database. Finally, rammed earth option was dismissed not because of a lack of data, but because it also acts as structure, exterior and interior finish, and thermal insulation. It became incomparable with the other entries.

As strained in the introduction, water infiltration can spell the end-of-the-line for a home while new construction products can take decades before showing signs of faulty design or mishandled installation. Architects may wish to consider the legal and ethical implications of emerging products that have not undergone a full life-cycle of practical on the market. The ensemble formed by the 3 categories should incorporate solutions from distinctive eras, of varying degrees of complexity, durability and performance, and be representative of the large spectrum of VCLs available in 2017.

3. “Fast Track” LCA Methodology

In this section, the environmental impacts “from cradle to grave” of some of the most common vapor control layers are analysed and compared using a simplified version of LCA. Also known as “Fast Track LCA” (TU Delft, 2017), this method was put forth by TU Delft for the specific use of designers and other users unspecialised in environmental assessments. Therefore, the calculations and other estimates contained in this section are based upon multiple presuppositions regarding the life cycle of the products analysed. Details and repercussions of these assumptions are addressed both prior to the calculations and in parallel with the results of the LCAs.

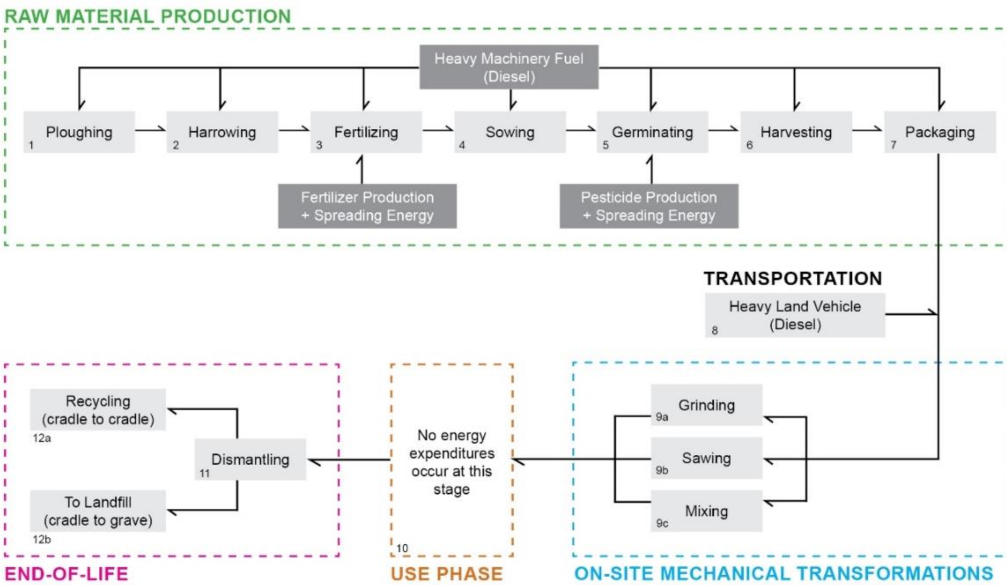
3.1. Functional Unit

All LCAs require a Functional Unit (FU) serving as a basis of comparison between critically different construction products and assemblies. In the present case, the LCA is conducted for a representative $1\ m^2$ of non-bearing exterior wall surface area (as described in the previous section). Consequently, the FU represents a unit of vertical surface measured immediately over the load bearing structure to which it is clad. This, in turn, implies that wall thickness is expected to vary in accordance with the products being analysed. A single square meter offers an order of magnitude for the calculations that can be intuitively visualized by most readers. Additionally, a review of the current literature reveals that this functional unit has been used successfully in anterior research into similar building assemblies (Pretot et al., 2014).

3.2. Boundary Conditions

Further, time-consuming calculations can be eliminated by accounting for redundant or controlled variables of the boundary conditions. Consider the following graphical representation of a Fast-track LCA that encapsulates the main production processes common to all the harvested materials in the upcoming analysis :

Figure 3. Graphical Representation of LCA, Valid for All Agricultural Materials Analysed in This Paper.



In a "standard" application of LCA methodology of a specific product, the boundary system typically traces back the origin and extraction process of every component or raw material involved as well as their location and importation costs. However, this method was formalized by manufacturers and other industrials for in-house assessments of their own products (SAIC, 2006). The latter thus assumes that information regarding the exact *provenance* of the raw materials, the machinery used, and the shipping costs are readily available to the researcher. In contrast, the analysis of a product by a third party may solely depend on the will of a manufacturer to divulge its well guarded trade secrets and list of subcontractors as is the case some of the previously cited research (Pretot et al., 2014). Hence, the multiplicity of products investigated in this report makes the aforementioned collaboration nigh impossible within the scope of the research and the time constraints of this report's format. Moreover, assemblies and construction techniques are not product-specific by *design*. For instance, the drawing of a wall section may dictate the use of a polyethylene housewrap of precise properties but not single out a specific manufacturer. In other words, even though polyethylene membranes may be regarded as its own type of vapor retarder, the spectrum of products it includes may present significantly different environmental impacts as a result of their manufacturers' distinct business practices.

Thankfully, the application of the Fast Track LCA combined with the readily available LCA databases Idemat and EcoInvent provide a methodological solution to the problems mentioned above. Indeed, previously conducted LCAs of more than 8000 materials, products, and processes are presented as averages by country, continent or globally. Hence, the data obtained from the latter two databases is already meant to be "representational" of the ensemble of business practices of any given region. Likewise, the absence of precise *provenance* for the materials in the databases must lead to other crucial assumptions in regards to the energy needed for transporting the materials to their construction site. As neither the location of the suppliers nor the construction site are given, calculations of fuel expenditures for transportation between both emplacements is impossible. Nevertheless, it remains possible to assess this parameter by assuming that all the material analysed will transit through the same path while using the same mode of transportation. This is only made possible because the LCA databases provides the average eco-costs for the production of a given product within a specific country (NL). Hence, specific transportation costs may only necessitate calculations when it can only be sourced outside the Netherlands. In most cases, the environmental burden of any given assembly type will be proportional to the mass of its components. Additionally, most of the assemblies depicted in this report use raw materials that are either used as-is or with on-site handling involving rudimentary electrical tools. As a result, the Fast Track LCA can be performed without first calculating the impacts of the raw materials themselves; this step has already been done. In most cases, only on-site transformations need to be calculated.

Similarly, the wall components that are not considered to be part of VCL, despite having a permeance and environmental impacts of their own, do not necessitate calculations. Indeed, the load bearing structure and inner wall finishing are assumed to be the same in every case, effectively making this aspect of the wall assembly redundant. From a strictly comparative basis, it does not affect the properties of the vapor retardant layer and therefore its effects may be substracted from both sides of the equation. Likewise, the exterior finishes may also be excluded from the calculations on the same basis. Nonetheless, cases where the vapor retarder may double as a cladding system are acknowledged in their respective analysis as the exclusion of additional finishes will certainly affect the wall's combined environmental impacts. Lastly, the Fast Track LCA's "cradle to grave" approach implies that all the products and assemblies investigated in this report meet their end without being re-used. Thus, the end-of-life scenario is further simplified by assuming that the materials will be separated (if possible) and either disposed of in a landfill or in a waste treatment plant.

4. Discussion

To best discuss the results of the LCAs, it is preferable to identify a "benchmark", or frame of reference, to provide a clear demarcation between the current paradigm in residential construction and its alternatives. In the case at hand, the dominant products on the market are without contest plastic membranes, also known as housewraps, and their LCA will thus exemplify the problems with current non-renewable VCLs.

4.1. Membranes – Polyethylene and Tar Felt

Case in point: housewraps are manufactured from polyethylene, a plastic derived from the refining of crude oil, machined into a thin flexible membrane. The latter can be micro-perforated to reach varying degrees of permeance. For the LCA calculations, the thickness of the film, its permeance, and volumetric density were obtained from academic sources and residential construction handbooks; a thickness of 0.15 mm and a density of 43 grams per m^2 were used (Nash, 2017; Allen et al., 2017). The control over the product's physical properties also guaranties important advantages for architects using housewraps. First, the product can be tested in a controlled laboratory setting and can thus be expected to perform accordingly. Second, housewrap manufacturing is internationally standardized and regulated which fosters confidence from insurers. For instance, the ASTM and ISO standards are prevalent in the United States and Europe respectively. Third, the product may conveniently be used in conjunction with a vented rain-screen system that further prevents capillary water movement through the wall assembly (Fisette, 2001; Holladay, 2000).

Figure 4. Fast Track LCA of a Polyethylene Membrane (housewrap).

POLYETHYLENE MEMBRANE

EcoInvent Code	Unit	Mass per m2	Description	Total Eco-Costs (€)	Human Health (€)	Exo-Toxicity (€)	Resource Depletion (€)	Carbon Footprint (€)	E-E per m2 (€)
A.130.04.111	kg	0.043	Idemat2017 PE (HDPE, High density Polyethylene)	1.141	0.031	0.064	0.803	0.243	0.049
D.120.01.208	kg	0.043	Extrusion, plastic film {GLO}| Alloc Rec, S	0.132	0.032	0.028	0.003	0.069	0.006
-	kg	0.043	Fine machining energy	0.032	-	-	-	-	0.001
F.130.04.341	kg	0.043	Treatment of waste polyethylene | Alloc Rec, S	0.359	0.005	0.003	0.001	0.178	0.070
								Total (€) :	0.126

Despite polyethylene having the highest eco-costs of all the materials investigated in this report - by a 65% margin with its second in rank - the simplicity of its in-factory transformations limits the expected increase in total production impacts to a nominal margin. However, the waste treatment of polyethene in a cradle-to-grave scenario presents a staggering augmentation of 0.07 euros per Functional Unit (FU), nearly doubling the total impacts of housewraps. Still, the total eco-costs of polyethylene membranes may have been significantly higher if not for their incomparable thinness (0.15 mm). As a result, the total amount of material needed per FU amounts to little above 40 grams. While their raw components may be unrenewable and highly damaging, housewraps provide a crucial “minimal size” advantage over their alternatives, effectively making them the most “sustainable” option analysed in this report despite not being fully renewable. This nuance can already be perceive in the resource depletion indicator of polyethylene; by itself, this indicator represents the majority of housewraps’ eco-costs. In short, plastic membranes may represent the solution of least impact for the moment, but their inevitable depletion make them ultimately transitional -but towards what?

Figure 5. Fast Track LCA of a 15# Natural Pitch Paper.

15# FELT PAPER

EcoInvent Code	Unit	Mass per m2	Description	Total Eco-Costs (€)	Human Health (€)	Exo-Toxicity (€)	Resource Depletion (€)	Carbon Footprint (€)	E-E per m2 (€)
A.120.01.202	kg	0.254	Idemat2017 Board and recycled paper ("test liner")	0.115	0.009	0.020	0.006	0.079	0.029
A.040.02.204	kg	0.356	Pitch {RoW}| market for pitch | Alloc Rec, S	0.118	0.015	0.046	0.003	0.054	0.042
F.060.01.101	kg	0.610	Idemat2017 landfill (inert waste, not biodegradable)	0.116	0.000	0.000	0.116	0.000	0.071
								Total (€) :	0.142

One possible alternative with identical advantages may be found in vernacular architecture. In the past, felt or paper was hand-coated until saturation with natural pitch to serve as “housewrap”. Similar products were subsequently developed using synthetic tar and Kraft paper which used to be referred to as 15# felt. While the appellation used to refer to the product’s density, namely 15 lbs/100ft^2, modern synthetic versions now use bitumen or asphalt over lighter paper (Holladay, 2000). To contrast with polyethylene membranes, the original organic version was considered for LCA as it represents a technically “bio-based” solution. To mimic the ancestral tradition, the calculations take into account that pitch is manually applied to the paper by craftsmen on-site, thus removing the necessity for mechanized transformations. Additionally, to remain compliant with the permeance criteria established in the research objective, the mass ratio between paper and pitch is assumed respect the standard for the original #15 felt (ASTM, 2017). In spite of these conditions, the LCA of natural pitch as a vapor control layer shows eco-costs that nearly doubles those of its polyethylene alternative. These counterintuitive results may be explained by the erroneous assumption that pitch, even if un-processed and acquired from a bog, is biodegradable (Reunanen et al., 1990). After all, pitch was historically selected for this very property: preventing rot and decomposition. Once combined, the paper and pitch may not be separated after their use. Consequently, the pitch prevents the biodegradation of the paper and the whole mass of the assembly must be considered "inert waste". The product must either be disposed of in a waste treatment plant for bitumen sheets (the most damaging possibility) or sent to the landfill (represented in the calculations). Without the subsequent increase in eco-costs due to the end-of-life scenario, traditional pitch and paper would have otherwise presented identical results to its ethylene counterpart. Moreover, the traditional application of pitch on paper on-site does not present the same degree of quality control against as a manufactured plastic product. It must nevertheless be pointed out that the heavy paper may absorb liquid water that condenses through on the interior side of the membrane and evaporate it outwards, a clear advantage over non-absorbent plastic films (Holladay, 2000).

4.2. Organic Infill – Straw-Bale Construction

Furthering the subject of vernacular vapor control layers, straw and reed have regained significant popularity over the last decade as an allegedly "sustainable" thermal and water insulation system. Also, the affordability and widespread cultivation of straw makes it an intuitively fitting candidate for the task at hand.

Figure 6. Fast Track LCA of a Straw-Bale Assembly.

STRAW-BALE CONSTRUCTION

EcoInvent Code	*Unit*	*Mass per m2*	*Description*	*Total Eco-Costs (€)*	*Human Health (€)*	*Exo-Toxicity (€)*	*Resource Depletion (€)*	*Carbon Footprint (€)*	*E-E per m2 (€)*
A.010.05.126	kg	49.75	Wheat straw, at farm/NL Economic	0.004	0.002	0.197	0.000	0.034	0.197
D.010.01.204	kg*	49.75	Baling {GLO}| market for | Alloc Rec, S	0.002	0.000	0.000	0.000	0.001	0.077
D.010.01.203	kg*	49.75	Bale loading {GLO}| market for | Alloc Rec, S	0.0001	0.0000	0.0000	0.0000	0.0001	0.003
F.060.01.102	kg	49.75	Idemat2017 landfill (biodegradable)	0.000	0.000	0.000	0.000	0.000	0.000
*Converted from tonnes to kg								**Total (€) :**	0.276

To be exact, straw-bale construction consists of non-load bearing straw infill of exterior walls complemented by a layer of finishes to prevent bulk water infiltration. It bears mentioning that straw bale construction, unlike other assembly types in this report, is *hygroscopic*, i.e. due to straw's porosity, it may absorb a higher degree of vapor and can thus accommodate permeable finishes (Straube, 2009; Magwood, 2016). Unfortunately, a rapid glance at the mass of the materials per Functional Unit reveals a sizeable problem: the quantities of minimal raw substance required to attain adequate insulation are staggeringly high compared to the previous entries in this analysis. Despite containing some of the least polluting materials of this report, the sheer density of the straw bales, 110 kg/m^3, combined with a minimal thickness of 450 mm caused the FU to contain nearly 50 kg of straw alone (Magwood, 2016; Straube, 2009; Fugler, n.d.). As a result, the total eco-costs of the production of unprocessed straw exceed that of polyethylene and pitch membranes. This is, of course, notwithstanding the environmental impacts of compacting the product into bales which represent as much eco-costs as the production and disposal of plastic housewrap. But how to explain this discrepancy between these results and the public's understanding of straw as "sustainable"? For one, the fact that the costs of depletion are null certainly demonstrate that the material is renewable *ad infinitum*. Yet, the carbon footprint of straw may provide the answer. Despite sequestrating carbon dioxide as part of its growth, the agricultural apparatus needed to maintain the cultivation of the plant may be unsustainable. The machinery used, the nature of the fertilizer, and the general business practices of the producers and distributors are activities responsible for aggravating the environmental burden of agricultural products. It is thus no surprise that on a global scale, agriculture is responsible for a much larger share of blame for climate change. Straw or reed may be organic by definition, but they are not grown *in* nature *by* nature when cultivated industrially. Thankfully, straw-bale construction *can* be made considerably more sustainable if it is integrated in the circular economy. Every year, millions of metric tonnes of straw are produced in excess by the industry (University of Manitoba, n.d.). Re-using this material would offset its eco-costs from 0.276 euros to a very competitive 0.079, the lowest result obtained in this report.

The inherent quality of straw and other similar materials to double as VCL *and* thermal insulation may provide a significant advantage over their alternatives. With a straw layer thickness of 450 mm, the thermal insulation provided may reach up to RSI 5, twice as much as the typical value of housing in northern countries (Fugler, n.d.). In fact, replacing the need for cellulose insulation, a material with significantly higher embodied energy than straw, may possibly offset the eco-costs difference if the complete wall assembly is considered (Mileto et al., 2017). Moreover, the added wall mass of the straw and plaster can generate energy savings by adding thermal as a passive heating-cooling system. The distance between the load-bearing studs and the exterior finishes also mitigates the effect of thermal bridges within the structure, further improving the energy efficiency of the home (Mileto et al., 2017). In short, given that straw can nullify the need for other thermal insulation and improve a home's energy efficiency, straw-bale construction can become a truly sustainable option when it re-uses the industry's surplus.

4.3. Composite Material – Hempcrete and Expanded Cork

It must now be considered that perhaps new material arrangements could provide the ideal vapor control layer. Since the 1990s, significant advances in material engineering have provided new, yet more complex, usage for familiar organic materials: composites materials. Where concrete and brick may prove too environmentally impactful, researchers have found new ways of replacing mineral aggregates with vegetal fibers to obtain a more "eco-friendly" alternatives with similar attributes.

Among a few, hempcrete blocks has garnered significant attention for its negative carbon footprint. The product is made by mixing industrial hemp shives (75%), fibers (20%), and dust (5%) along with a chemical binder, and then placed into moulds, typically by hand (Dhakal et al., 2017), then cured (Arrigoni et al., 2017). The hemp plant, a less potent strain of *Cannabis Sativa*, shows the clear advantage of being grown in the Netherlands and with "little to no pesticides" and a "modest" need for fertilizer (Van der Werf, 2004). The manufacturing process is waste-less since defective or decrepit blocks can be re-incorporated into the mixture and moulded again (Arrigoni et al., 2017). Additionally, the curing block continues to sequestrate carbon dioxide, which pushes its carbon footprint even further into the negative (Pretot et al., 2014). The hempcrete block, similar in appearance and texture to concrete, is a non-structural component that may serve as an exterior cladding with adequate permeance, that is, depending on the thickness of the hempcrete layer and its density. The latter may vary significantly between manufacturers and studies alike as numerous hemp-to-binder ratios exist on the market. For this report, only a single composition has been scientifically confirmed to satisfy the permeance criteria of Section 2: a 430 kg/m^3, 25 cm thick block with a hemp-to-binder ratio of 1:1.3 (Dhakal et al., 2017). However, no data was found for hemp in neither the Idemat nor the EcoInvent databases. As it should be expected for recent technology, credible and peer-reviewed data remain scarce as research and experiments have yet to coalesce into its own standardized sector of activity as for housewraps, cement, and many more widespread materials. A *complete* Fast-Track LCA using eco-costs is thus currently impossible. Yet, other studies have assessed the environmental impacts of hempcrete using different indicators (Van der Werf, 2004). It was thus possible to convert the data of some impact categories into eco-costs.

Figure 7. Partial Fast Track LCA of Hempcrete.

HEMPCRETE

EcoInvent Code	Unit	Mass per m2	Description	Total Eco-Costs (€)	Human Health (€)	Exo-Toxicity (€)	Resource Depletion (€)	Carbon Footprint (€)	E-E per m2 (€)
-		56.087	Hemp (core, fiber, dust)	-	0.016	0.021	0.000	-0.201	-
D.150.03.211		56.087	Wood chipping, stationnary | Alloc Rec, S	0.003	-	-	-	-	0.191
A.040.01.102	kg	14.583	Idemat2017 Cement (Portland)	0.128	0.007	0.015	0.004	0.102	1.860
A.110.01.208	Kg	58.33	Dolomite {GLO}| market for | Alloc Rec, S	0.011	0.003	0.003	0.000	0.005	0.668
D.115.01.212	kg	129.00	Plaster mixing, by hand (traditional method)	0.000	0.000	0.000	0.000	0.000	0.000
								Total (€) :	2.72

The information contained in the LCA calculation table, carbon footprint excepted, only accounts for some environmental impacts. For instance, the eco-costs of human health is missing the impacts of fine dust and photochemical oxidants. As a result, the true health costs may be higher than represented. While a pronouncement on total eco-costs is unadvisable, distinctions between hempcrete and other products can still be drawn. Specifically, the carbon sequestration potential of hempcrete, embodied here by the total negative carbon footprint, could likely render hemp effectively eco-cost neutral or negative. Although not all impact categories could be determined, the incomplete values are still expected to be lower than that of a similar, yet certainly more damaging, crop: cotton (Van der Werf, 200). In other words, it can be asserted with quasi-certainty that even if hemp was as damaging as cotton, the negative eco-costs for its carbon footprint would average the total eco-costs to zero or potentially less (Arrigoni et al., 2017). Unlike straw bale construction where low impact materials amount to large environmental costs due to their staggering mass, a null total eco-cost for hemp would imply no eco-costs regardless of quantities. Of course, the same cannot be said about the transformative processes nor the binder material. By far, the greatest contributor to hempcrete's impacts is its cement binder (Pretot et al., 2014) and dolomite lime. Whether or not the hempcrete block's total eco-costs are offset by hemp's stellar performance remain unknowable for the case at hand. Regardless, other research teams have already proposed alternatives to cement, although more research is thoroughly needed to corroborate the findings of isolated studies.

Figure 8. Fast Track LCA of Expanded Agglomerated Cork.

EXPANDED AGGLOMERATED CORK (NO FINISHES)

EcoInvent Code	Unit	Mass per m2	Description	Total Eco-Costs (€)	Human Health (€)	Exo-Toxicity (€)	Resource Depletion (€)	Carbon Footprint (€)	E-E per m2 (€)
A.160.09.108	kg	14.69	Idemat2017 Cork granulate glued = aggregate	0.249	0.024	0.050	0.051	0.124	3.66
								Total (€) :	3.66

Identical problems are also prevalent for the last vapor control product of this report: expanded agglomerated cork (EAC). Much like hempcrete, EAC is an emerging composite material that mimics the recipe of concrete, but with the addition of cork. Likewise, the harvested cork, native of North African and Middle-Eastern countries, is grinded, mixed with a lime and cement binder, moulded, and cured into a block or thick insulation panel. Unsurprisingly, the flaws of hempcrete are mirrored by EAC, if not exacerbated, by the fact that cork's cultivation is limited to distant regions from the

Netherlands and that, unlike hemp, it does not sequestrate additional carbon dioxide. Thankfully, eco-costs for EAC are readily available in the EcoInvent database for the finished products. For an approximate density of 186 kg/m^3, EAC panels must present a minimal thickness of 80 mm per Functional Unit to attain the required permeance. Assuming that cork may by attached to the wall assembly with only four drops of No-Nail, LEED certified, glue (Rosetta et al., 2015), and that recent projects have shown that it may be used without additional protective coating outside (SEASuperhomes, 2012), the LCA was conducted with considering the eco-costs of the finished product only with no subsequent transformations. However, due to the mass of the slab and the ecological burden of concrete, EAC's eco-costs per FU far outweigh any other vapor control layer with 3.65 euros/m^2 of insulated wall. Ultimately, the possibility of parting with exterior finishes altogether is a small advantage considering that sustainable, low impact, claddings are already well know and available, i.e. wood siding, clay plaster, etc. Additionally, the added thermal insulation of the cork and hempcrete layers have yet to be accurately measured, unlike straw-bale construction, meaning that some insulation might still be needed. Again, only a full LCA analysis of a complete home's envelope, including its energy expenditures caused by its occupants, could provided a definitive recommendation for EAC. Inversely, straw-bale construction offers better efficiency and a more robust documentation.

5. Conclusion

In summary, harvested construction materials present the double-edged characteristic of requiring simple and unimpactful transformations. As such, the majority of their environmental burden lays on the production of the raw materials themselves. For the latter, it remains advantageous to obtain "leftovers" or products that would otherwise been thrown away. Straw bale construction, for instance, despite its high eco-costs highlighted in the discussion, may benefit from the 17.7 million metric tonnes of surplus straw in the U.S. alone (University of Manitoba, n.d.). There is most certainly a place for bio-based vapor control layers as part of a circular economy. Yet, the prospect of large scale production of agricultural building materials for a systematized construction system remains vehemently unadvisable. After all, agricultural activities are responsible for greater environmental impacts than all construction activities globally combined. It must be kept in mind that the production of fertilizer for the crops, the operation of heavy machinery, the packaging, and the distribution of harvested products are not yet fully sustainable practices. The transition towards un-depletable, fully renewable harvested materials can only be initiated if manufacturers, scientists, and designers, through their combined efforts, manage to: **a.** Reduce the quantity of materials necessary to achieve adequate insulation; **b.** Find alternatives to cement and other high-energy binders in composite materials; **c.** And ameliorate the resource efficiency of our current agricultural practices.

The merging of sustainability and renewability continues to present fundamental challenges that can no longer be ignored. Despite the numerous assumptions inherent to Fast Track LCA methodology, an order of magnitude between impact categories can nevertheless be discerned between the products and assemblies reviewed in this report. For the time being, synthetic solutions will generally remain the choice of least impact for architects who strive for sustainability.

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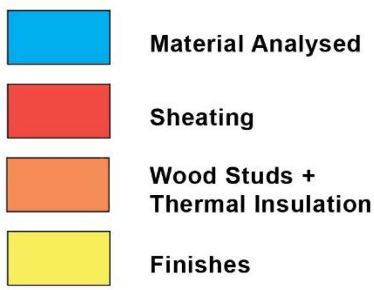
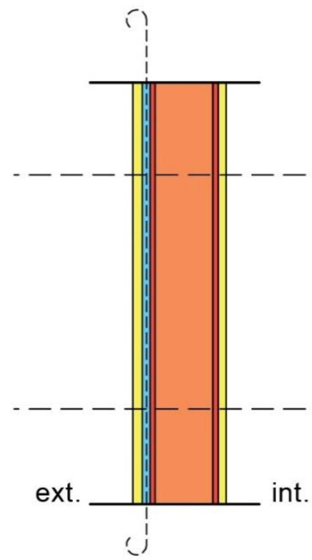
Appendix

The following diagrams illustrate the wall assemblies in respect to the materials analysed in the discussion. The gap between the dashed horizontal lines represent the size of the Functional Unit described in Section 3. Further, it can be observed that certain layers are redundant among the diagrams, like sheathing, which is why these elements are not calculated as part of the comparative analysis.

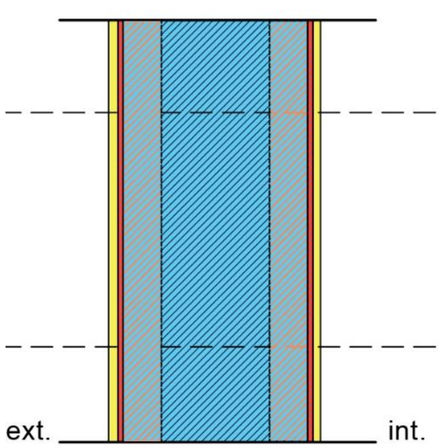
Legend



Polyethylene and Tar Felt



Straw-Bale Construction



Hempcrete and Expanded Cork