

ENVIRONMENTAL AND PERFORMANCE ASSESSMENT OF PROTECTIVE OUTER LAYERS FOR PAPER-BASED BUILDING ENVELOPES

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Received: 28.05.2024; Revised: 12.12.2024; Accepted: 14.01.2025

Abstract

Paper-based building components can lead towards more sustainable, energy-efficient, affordable structures. Building envelope is one of the most common areas for the application of paper in architecture. However, paper-based envelope requires an outer layer protecting it against water, fire and mechanical damages, which may significantly increase the components' environmental impact, weight and manufacturing costs. The article review fourteen original outer layers design proposals, suitable for use on indoor, outdoor and roof surfaces. All the designs combine various protective materials and complementary coating techniques. The environmental impact of proposed designs is assessed via Life Cycle Assessment analysis based on Ecoinvent 3.8 database. The proposals' performance is assessed in the areas of water, fire and mechanical damage protection, materials cost and availability. Designs with high-performance scores and low environmental impact are indicated for both indoor and outdoor applications. As a conclusion from the research, guidelines and suggestions for further development of paper-based building envelopes are provided.

Keywords: Building envelope; Life cycle assessment; Paper; Fire protection; Water protection

1. INTRODUCTION

Paper, a material which was invented by humankind in the first century A.D. is one of the most common and popular materials these days [1]. Next to its primary function – an information carrier, paper is utilised in various applications, especially for packaging, but also furniture and even architectural structures such as temporary pavilions, emergency shelters, houses and public buildings [1, 2].

Paper and cardboard are the main packaging material in Europe, and they are used twice more often as subsequent plastic and glass [3]. Moreover, the recycling ratio of paper and paper board reaches over 70% in the last 7 years [4]. Paper industry, however, is constantly looking for new applications and

possible expansion to new, unrecognised business areas [5].

The key feature of paper, and paper-based products, such as cardboard is their natural origin. Paper is a network of cellulose fibres, which are intertwined. During the production, the hydrogen bonds between cellulose fibres are created under the pressure, in a wet environment. The bonds affect the mechanical properties of the material. For that reason, the best products in structural applications are those free of impurities and other components such as hemicellulose and lignin. However, the production of strong paper (Kraft) is energy – and water intensive and it requires virgin fibres, preferably as long and slender as possible.

As the hydrogen bonds are created in a wet environment, water and humidity may have the reverse effect i.e., loosen them, causing in softening of the paper or, in the ultimate case, turning it back into a pulp. This feature has both, positive and negative influences on paper and cardboard properties, especially in architectural applications. On one hand, it allows to recycle of the material up to 6 times [6], on the other hand, it causes a risk to structural stability.

Therefore, it is of high importance to adequately waterproof paper-based products which are utilised in architectural applications, especially when exposed to natural conditions. The most popular ways of damp-proofing are coating with polyurethane paints and epoxy resins [1], or polyethene coating [6]. Those, however, make paper impossible or very difficult and hence expensive to recycle.

The other issue is combustibility of paper products. When utilised in thick elements paper can achieve non-flammability, but in turn, this significantly affects its weight and thus, the cost of production, transport and treatment. Rodents, fungi and microorganisms can also cause problems.

Paper is, therefore, a promising eco-friendly material for architectural applications, but must be treated in an appropriate manner to minimise the impact of moisture, fire and organisms, while still being recyclable.

2. PAPER-BASED BUILDING ENVELOPES

Building envelope, understood as enclosure of indoor building space from the external environment, in particular a non-loadbearing external wall, is an essential part of the vast majority of architectural structures [7]. Most lightweight envelopes are manufactured as sandwich elements, with a thick, insulative internal layer and thin protective outer layers on both sides. Envelope is also one of the most popular applications of paper in architecture [8]. Products such as corrugated cardboard and paper honeycomb panels offer an appealing combination of thermal insulation properties, structural stability, availability and low environmental burden. However, to meet safety and performance requirements, a combustible and humidity-sensitive core must be accompanied by durable outer layers. The desired protection may be achieved using various protective techniques or their combinations, including lamination with polymer foil (FL), varnish coating (VC), additional layers of durable non-paper materials (AM) and paper material modification during production (MM) [8].

Several paper-based building envelopes have been designed, constructed and tested in the last decades, featuring various protection techniques (see Table 1).

Table 1.
Characteristics of paper-based envelopes case studies.

		Westborough PS	Wikkellhouse	TECH 03 (House of Cards)	TECH 04	FPPH
designers		Cottrell and Vermeulen Architecture	Rene Snel, Fiction Factory	Jerzy Łatka, Marcel Bilow, Julia Schönwälder,	Jerzy Łatka, Agata Jasiolek	TU Darmstadt BAMP! group
life span (assumed)		20 years	50 years	5 years	5 years	minimum 3 years
Outdoor surface	Protection technique	FL, AM	FL, AM	FL	FL, AM	FL, MM
	materials	breather membrane, fibre-cement board	breather membrane, wood cladding	self-adhesive foil, polyethene-coated paper	aluminium sheet	polyethene-coated paper, paperboard
	combustibility	non-combust.	no data	combustible	non-combust.	semi-combust
	water resistance	watertight	watertight	watertight	watertight	watertight
	mechanical damage resist.	high	high	low	moderate	moderate
Indoor surface	Protection technique	AM	AM	FL	FL	FL, MM
	materials	FR cellulose pin-board	plywood	self-adhesive foil, polyethene-coated paper	self-adhesive foil	polyethene-coated paper, paperboard
	combustibility	non-combust.	no data	combustible	combustible	Semi-combust
	water resistance	moderate	moderate	watertight	watertight	watertight
	mechanical damage resist.	moderate	high	low	low	moderate

The social building of Westborough Primary School, which was the first permanent paper-based building in Europe, added layers of fibre-cement boards and fire-retardant cellulose pinboard in its envelope [1, 9]. Also, the project of Wikkellhouse, a prefabricated corrugated cardboard holiday house, opted for AM protection, where plywood and wood cladding was used [1, 10]. On the other hand, Transportable Emergency Cardboard Houses No 3 and 4 used mostly lamination with self-adhesive foil, a quick, lightweight but prone to damage solution [1, 8]. The Full Performance Paper House present a different approach, incorporating various types of speciality paper into envelope design, including fire retardant, high density and waterproof, polyethylene-coated one [11]. It should be also noticed, that all the longer life-span envelopes include an air cavity, forming a ventilated façade, that prevent water vapour condensation inside the material.

Moreover, various theoretical designs of outer layers have been proposed. Vaccari suggested coating the envelope with painted recycled drink cartons (an approach similar to FPPH) [12], while the author of this article used a polyvinyl chloride-coated textile in previous projects [8]. A series of walls and partitions were proposed by Ayan, featuring finishing materials such as aluminium plate, metal or wood cladding, plywood, gypsum plasterboard or even glass [13]. On the contrary, another series of envelopes was proposed by Bach, with thick paperboard cladding in various sizes and arrangements [14].

Protective techniques for paper-based building elements

Although protection against destructive factors is crucial for paper-based building elements, it may also significantly increase its environmental impact, weight and manufacturing costs. Therefore, the use of bio-based and recyclable materials is highly recommended. Two main groups of protective techniques are coatings and impregnation (including paper modification during production) and non-paper finishing materials (including foil lamination).

Coatings and impregnation

Due to its porous structure, paper is a material that is easy to coat with coating materials. During spreading, the coating penetrates into the pores of the paper causing its anchorage. Protective coating materials include polymeric resins such as epoxies, polyurethanes, polyacrylates, or formaldehyde resins. They form tight and durable coatings that prevent moisture from penetrating deep into the paper, thus weakening its properties. The coatings can also provide fire protection by blocking access of flames to the paper, or by decomposing into fire-resistant compounds during combustion. To achieve such effects, additives called flame retardants are added to resins, which include such compounds as metal oxides and hydroxides, boron, silicon, and halogen compounds [15, 16]. Another effective way to protect paper is to impregnate it with non-coating materials like waxes and oils, which can improve the hydrophobicity of produced paper elements [17]. A range of coating and impregnates suitable for use on paper-based elements can be found in Table 2.

Table 2.
Coatings and impregnates for paperboard

Product and manufacturer name	Base material	Water resistance	Fire resistance	UV degr. resistance	Price	Recyclability of coated paper
Monovar PU varnish	polyurethane	low	low	high	high	moderate
Sadolin Yacht Varnish	alkyd resin	high	low	high	moderate	moderate
Jedynka Wax Varnish	alkyd resin, polysaccharide resin and linseed oil	low	low	high	low	moderate
Bird Brand Complete Decking Oil	natural oils, waxes and resins	high	low	moderate	low	low
Timberex hard wax oil	natural oils and waxes	high	moderate	moderate	high	low
Colorit wood wax	synthetic and natural waxes	moderate	low	moderate	low	moderate
Dragon linseed oil varnish	linseed oil	high	low	high	low	low
COO-VAR Siliconized Teak Oil	natural oils and silicone oil derivatives	moderate	moderate	moderate	low	low
Sicol Sodium Water Glass	sodium silicate	-	high	-	low	high
Burnblock	natural occurred compounds	-	high	-	moderate	high
Borates fire retardant	sodium borate-boric acid 1:1 mixture	-	high	-	low	high

Polymer coatings made from non-renewable sources are extremely increasing the ecological impact of paper. By using these protective materials layered structures are made, and their recyclability is harder. Year by year materials and techniques with less environmental impact is being investigated as protection of paper elements, which reduces the harm to the environment. As a substitute for polyolefins protection biodegradable polymeric materials are being used to cover the paper surface, for example, poly(lactic acid), PLA, or polyhydroxyalkanoates [18].

Non-paper finishing materials

The second group of protective techniques are non-paper finishing materials. There are many different types of materials such as metal sheets, plywood, fibre-cement and HPL board, membranes, fibreglass wallpaper, vinyl veneer, etc. Protective materials may be combined with various coating, to obtain a finishing layer with desired properties. Products such as HPL (high-pressure laminate) or fibre-cement board, thanks to their high damage resistance can be used on vertical outdoor surfaces. On the contrary, lightweight materials like fibreglass or polyvinyl chloride veneer can provide sufficient and low-cost protection for partition walls. Significant differences can be observed in the environmental burden caused by each of the finishing materials. A range of materials suitable for use as protective layers in paper-based building envelopes is presented in Table 3.

Aim of the research

Protective outer layer is an indispensable part of every paper-based building envelop. With an efficient

design, it can provide water tightness, fire resistance and mechanical damage resistance, without compromising the envelopes environmental properties. Despite that, the issue of a protective outer layer had a minor role in most of the previously conducted research, which usually opted for conventional solutions such as wood cladding or foil lamination. In order to facilitate and popularise the use of pro-ecological paper-based building envelopes, the outer layer design should be studied and evaluated it terms of ecological impact.

Therefore, the aim of the research is (i) to review a group of original outer layers designs, suitable for use on indoor, outdoor and roof surfaces, (ii) to evaluate their resistance to various destructive factors, (iii) to assess the environmental impact of proposed designs, and (iv) to select the most appropriate designs for various applications. As a conclusion from the research, guidelines and suggestions for further development of paper-based building envelopes are provided.

Materials and methods

The research was conducted on fourteen outer layer designs with various levels of damage resistance. Data about the designs served as input for Life Cycle Assessment analysis, which led to the final evaluation.

Materials and designs under study

A series of outer layers for paper-based cores was designed, based on a literature review, material characteristics and authors' experience from previous research and works with paper architecture.

Table 3.

Finishing materials proposed for use on paper-based building envelopes. ¹ low price – less then 25€ per m², moderate – 25-50€, high – over 50€. Estimated based on market prices in Poland in 2022

Material	Thickness [mm]	Weight [kg/m ²]	Fire resistance	Water resistance	Mechanical resistance	UV degr. resistance	Price ¹	Recyclability
aluminium sheet	0.60	1.50	high	high	low	high	low	high
plywood	18.00	10.80	moderate	moderate	high	moderate	high	moderate
fibre-cement board	10.00	13.20	high	high	high	high	low	moderate
HPL board	5.20	2.68	high	high	high	high	high	low
EPDM membrane, FR	1.80	2.45	high	high	high	high	low	high
PVC membrane	1.80	2.50	low	high	high	high	low	moderate
fibreglass wallpaper	0.50	0.05	high	high	high	high	low	low
vinyl veneer	0.50	0.75	moderate	high	high	high	low	moderate
carbonised timber	20.00	11.00	moderate	moderate	high	high	high	moderate
magnesium oxide board	8.00	8.00	high	high	high	high	high	moderate
gypsum board	12.00	8.06	moderate	low	moderate	no data	low	moderate
bitumen shingle, FR	2.00	10.00	moderate	high	high	high	low	low

Proposals cover seven layers for outdoor surfaces, including three suitable for roofs, and seven for indoor surfaces, for both dry and humid rooms.

A set of principles was followed in the design process. Each design should form a non-combustible finishing layer, to prevent the spread of fire through the surface and slow down fire penetration into the envelope. All the designs suitable for outdoor conditions should feature ventilated air cavities, to avoid water

vapour condensation inside the structure. Each design should provide water and humidity protection – water tightness for roof finishes, high water resistance for outdoor and wet room envelopes and moderate resistance for indoor, and dry room finish. All the designs have to be resistant to mechanical damage, however, the outdoor layers should provide high resistance level, while for indoor ones moderate resistance is sufficient. The proposed designs should

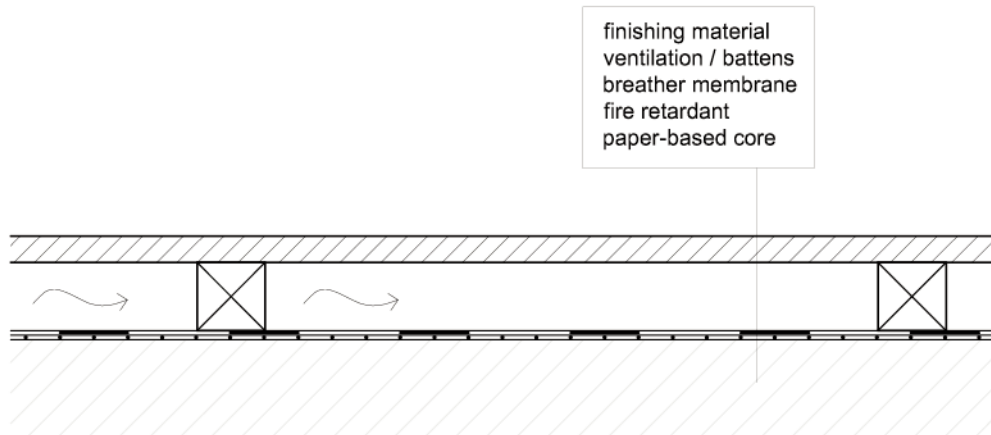


Figure 1.
Scheme of the outdoor outer layer

Table 4.
Characteristic of outdoor surface outer layers. BM+VC is a breather membrane and ventilation cavity

No	Layer scheme	materials	application	Thickness [mm]	Weight [kg/m ²]	Fire resistance	Water resistance	Mechanic. resistance	UV deg. resistance	Recyclability
E1		- HPL board, FR - BM + VC - Burnblock	wall	36.5	2.98	moderate	moderate	high	high	low
E2		- fibre-cement board - BM + VC - Burnblock	wall	38.5	13.50	high	moderate	high	high	moderate
E3		- FR wood varnish - plywood - BM + VC - borates	wall	45.5	10.95	moderate	moderate	moderate	moderate	moderate
E4		- carbonized wood - BM + VC - Burnblock	wall	50.5	4.80	moderate	moderate	moderate	high	moderate
E5		- coated aluminium - Burnblock - OSB/MDF board - BM + VC - Burnblock	wall and roof	41.0	7.88	high	high	high	high	high
E6		- EPDM membrane, FR - OSB/MDF board - BM + VC - borates	wall and roof	42.5	8.83	moderate	high	high	high	high
E7		- bitumen shingle, FR - OSB/MFP board - BM + VC - borates	wall and roof	42.5	16.90	moderate	high	high	high	low

Table 5.
Characteristic of indoor surface outer layers

No	Layer scheme	materials	application	Thickness [mm]	Weight [kg/m ²]	Fire resistance	Water resistance	Mechanic. resistance	UV degr. resistance	Recyclability
I1		- FR wood varnish - plywood	dry rooms	6.0	6.30	moderate	moderate	moderate	moderate	moderate
I2		- dispersion wall paint - Magnesium Oxide board - Timberex oil varnish	dry rooms	8.0	8.30	high	low	moderate	high	low
I3		- PVC veneer - paperboard - Burnblock	wet rooms	6.0	0.89	low	moderate	low	high	moderate
I4		- dispersion wall paint - fibreglass wallpaper - teak oil coating - paperboard - Burnblock	dry rooms	6.5	1.00	moderate	low	low	high	low
I5		- PVC membrane, FR - paperboard	wet rooms	7.0	3.00	moderate	moderate	low	high	moderate
I6		- dispersion wall paint - gypsum board - linseed oil varnish	dry rooms	12.0	8.36	high	low	moderate	high	low
I7		- HPL board - Burnblock	wet rooms	6.0	2.98	moderate	moderate	moderate	high	low

be environmentally optimised, thus incorporating natural, recycled and recyclable materials and allowing for their separation at the end-of-life phase.

Each outdoor outer layer design uses a general scheme of fire retardant, breather membrane, wooden battens with a ventilated air cavity in between and finishing layer composed of various non-paper boards (see Fig. 1). Materials used for roof-appropriate designs are aluminium plate, EPDM (ethylene propylene diene monomer) membrane and bitumen shingle on wood-based sheathing. For external wall – fibre-cement boards, HPL (high-pressure laminate) boards, coated plywood and carbonised wood were chosen. The characteristic of each design can be found in Table 4.

On the contrary, part of designs for indoor spaces is based on paperboard (that provides stiffness and certain fire protection [6]) with various types of laminates and coatings. The paperboard is coated with polyvinyl chloride veneer or membrane and painted fibreglass wallpaper. For more durable designs – HPL, plywood, gypsum and magnesium oxide boards were used. The characteristic of each design can be found in Table 5.

LCA analysis

Life Cycle Assessment is currently the most recognised and widely used method to evaluate the impact on the natural environment generated by products or services [19]. LCA methodology allows assessment over the entire life cycle, from the extraction of raw materials, through manufacturing and use, to end-of-life disposal or recovery. However, it may also be used to assess the impact in the cradle-to-gate scenario, which is often beneficial for decision-making during manufacturing. The principle of the LCA methodology is collecting data regarding the exchanges between the natural environment and Technosphere (called elementary flows) i.e. raw materials extracted and substances emitted to water, air or ground. This information is the input data for environmental burden calculations [20].

LCA analysis is regulated by standards ISO 14040 and ISO 14044, which divide the process into four stages: goals and scope definition, life cycle inventory analysis, and life cycle impact assessment and interpretation [21, 22].

Goals and scope

The aim of the analysis is to assess the environmental impact of a series of protective outer layers that may be used on paper-based building envelopes, providing

protection against humidity, water, fire and mechanical damage. Layers for indoor and outdoor applications are evaluated separately. The functional unit for all of the analysed case studies is 1m² of the protective layer. The study will indicate designs with the lowest environmental burden, that may be recommended for further development and real-life applications in architecture.

The scope of the analysis was defined in accordance with EN 15804 standard, which regulates LCA for building products. The document distinguishes four main stages of the analysis, which are: the products stage (A1-A3), construction process stage (A4-A5), use stage (B1-B7) and end-of-life stage (C1-C4) [23]. Considering limited data availability and accuracy, the discussed analysis was conducted in the 'cradle-to-gate with options' approach, covering stages A1-A3 and C2-C4. Furthermore, it should be noted, that additional connecting elements, that may be necessary for the assembly of the designed layer are excluded from the study, as the assembly techniques

may vary depending on the envelope core or building design.

Life Cycle Inventory

The life cycle inventory for each of the outer layers was prepared based on provided designs and technical data from material manufacturers, using the Ecoinvent 3.8 database in the OpenLCA software. Ecoinvent is an extensive database, focused on the European context, providing data regarding industrial processes, including wood and paper industry [24, 25]. The material inventory for analysed designs is presented in Tables 6 and 7.

The following assumptions have been made in the area of recycling and waste treatment:

- paperboard used made from 100% recycled fibre and 90% of the material is recycled at the End of Life phase;
- the remaining waste is disposed of in accordance

Table 6.

Material inventory of the analysed outdoor outer layers, presented in kg per average m² of the envelope

	E1	E2	E3	E4	E5	E6	E7
timber	2.160	2.160	2.160	13.160	2.160	2.160	2.160
plywood	-	-	10.800	-	-	-	-
fire retardant (borates)	0.150	0.150	0.150	0.150	0.300	0.150	0.150
acrylic varnish	-	-	0.150	-	-	-	-
breather membrane (polypropylene)	0.150	0.150	0.150	0.150	0.150	0.150	0.150
HPL	2.680	-	-	-	-	-	-
fibre-cement board	-	13.200	-	-	-	-	-
OSB board	-	-	-	-	7.800	7.800	7.800
EPDM	-	-	-	-	-	2.450	-
aluminium	-	-	-	-	1.500	-	-
bitumen	-	-	-	-	-	-	10.000

Table 7.

Material inventory of the analysed indoor outer layers, presented in kg per average m² of the envelope

	I1	I2	I3	I4	I5	I6	I7
plywood	3.600	-	-	-	-	-	-
fire retardant (borates)	-	-	0.150	0.150	-	-	0.150
acrylic varnish	0.150	-	-	-	-	-	-
dispersion paint	-	0.150	-	0.150	-	0.150	-
HPL	-	-	-	-	-	-	2.680
Fibreglass	-	-	-	0.050	-	-	-
Gypsum plasterboard	-	-	-	-	-	8.060	-
MgO board	-	8.000	-	-	-	-	-
PVC	-	-	0.240	-	2.500	-	-
paperboard	-	-	0.500	0.500	0.500	-	-
oil varnish	-	0.150	-	0.150	-	0.150	-

with standard waste management methods in Poland.

Life cycle impact assessment

To increase the accuracy of the results, two different impact assessment methods were implemented: CLM 2001 and ReCiPe. The CLM 2001, which follows the EN 15804 standard, is a midpoint method of evaluation, i.e. it focuses on quantifiable, direct impact, linkable to specific emissions. The impact was assessed in seven categories: global warming, ozone layer depletion, photochemical oxidation, acidification, eutrophication, fossil fuel abiotic depletion, and elements abiotic depletion. On the contrary, ReCiPe is one of the endpoint methods, also called damage-oriented ones, that translates midpoint impact into endpoint results, e.g. damage to the ecosystem or human health. The ReCiPe results are also presented as a single indicator, allowing direct comparisons between evaluated scenarios [26–28].

3. RESULTS AND DISCUSSION

Results of the Life Cycle Assessment analysis were combined with the performance scores of each outer layer proposal. The obtained data allowed for indica-

tion of the most beneficial design variants from each layer group.

3.1. Life cycle assessment

The conducted Life Cycle Assessment analysis revealed significant differences in the scenarios' environmental burden. As was to be expected, there is a visible positive correlation between the layer weight and its impact on the natural environment. In the case of roof-appropriate layers, the most favourable result was obtained in variant E5, using aluminium sheet. On the contrary, the impact of layer E7, with bitumen shingle doubled the results of all the analysed scenarios. Considering all the outer layers, the lowest impact can be linked to carbonised wood and HPL variants (E4 and E1). In ReCiPe analysis, for most of the cases, the largest share of total impact is located in the area of human health, and human toxicity in particular. However, the category of agricultural land occupation (ecosystem quality area) also plays an important role, mostly due to timber consumption (see Fig. 2). As presented by CLM analysis (see Fig. 3), the energy consumption from fossil fuels varies between 31 MJ for E4 to 474 MJ for E7 variant, and the carbon dioxide emission from 2.8 kg (E4) to 38.4 kg (E7).

Exterior envelope layers LCA results, ReCiPe method

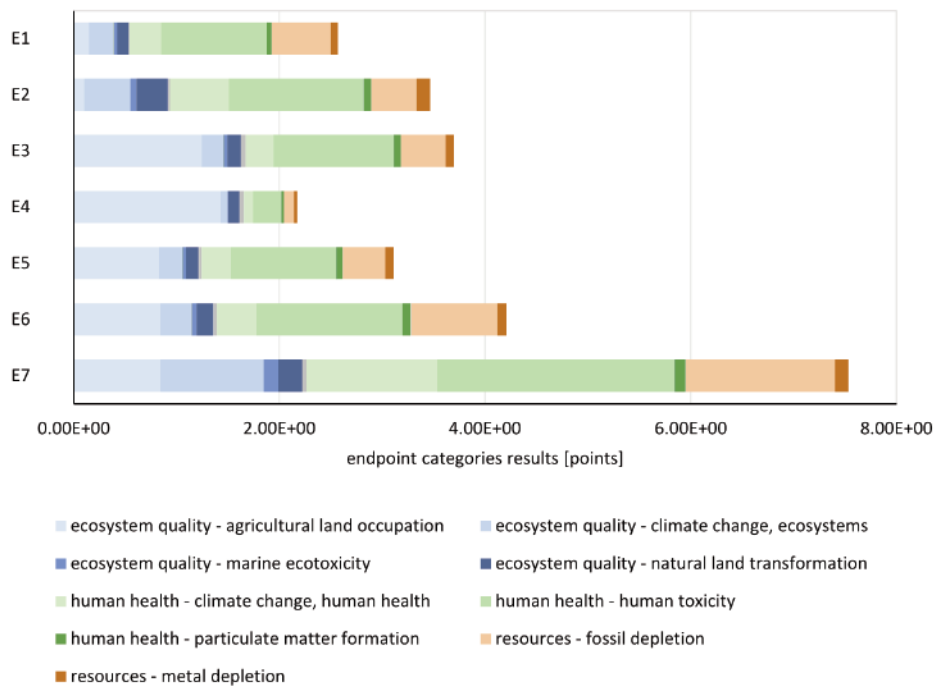


Figure 2.
Result of ReCiPe method endpoint LCA analysis for exterior layers E1-E7

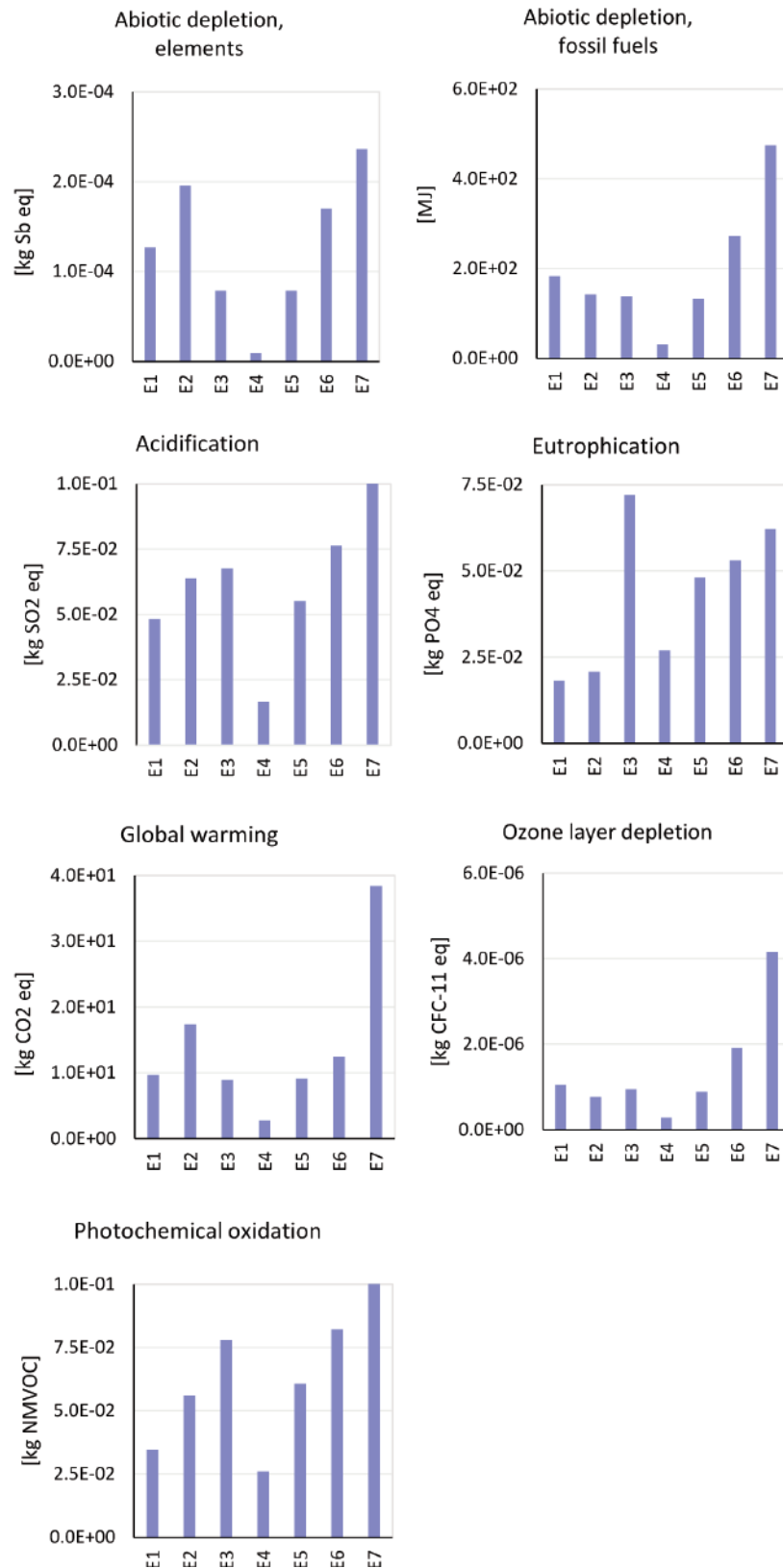


Figure 3.
Result of CLM 2001 method midpoint LCA analysis for exterior layers E1-E7

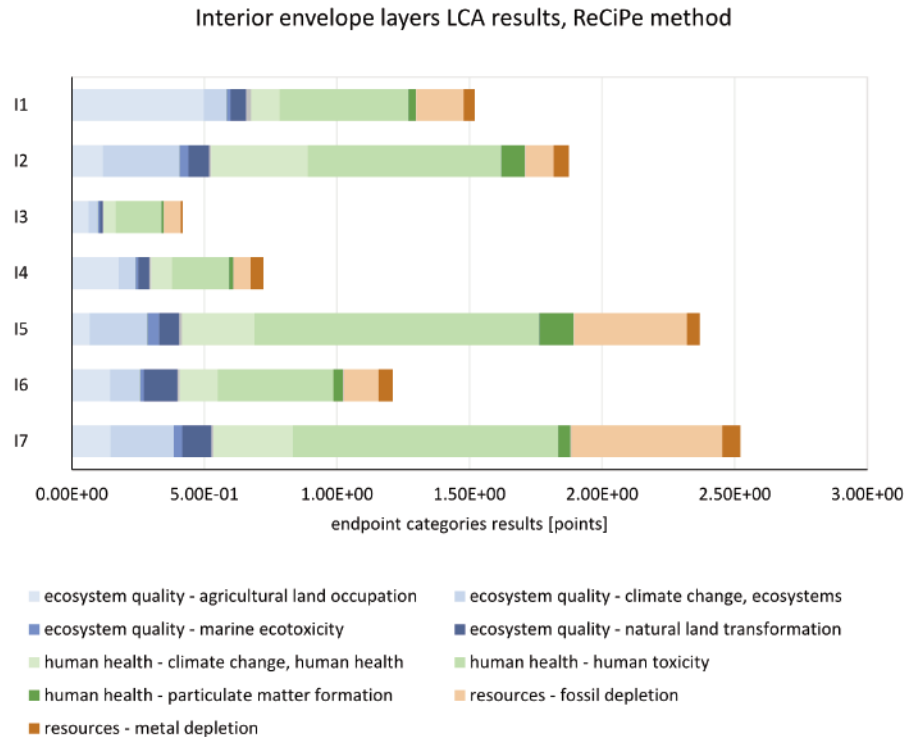


Figure 4.
Result of ReCiPe method endpoint LCA analysis for interior layers I1-I7

A large discrepancy in results was observed in the interior layer analysis – from 0.42 (I3 variant) to 2.52 (I7) in the ReCiPe single indicator results. The highest burden was associated with designs containing the largest amounts of petroleum-derived polymers, which are I5 with PVC membrane and I7 with HPL board. On the other hand, the most lightweight variants I3 (PVC veneer) and I4 (fibreglass) can be linked with the lowest impact. As with exterior layers, the most significant impact category in the endpoint analysis was human health – human toxicity (see Fig. 4). In the categories of midpoint analysis, a bigger variety was observed (see Fig. 5). The energy from fossil fuels consumption varies from 21 MJ (I2 and I3) to 182 MJ (I7), and the carbon dioxide emission –

from 2.0 kg (I3) to 10.9 kg (I2).

Outer layers evaluation

Based on materials characteristics the design performance was assessed, with the highest score among roof layers for E5, among external walls – for E2, among interior dry room – I6 and wet room – I3 and I7 (see Table 8). Secondly, the performance score was juxtaposed with single-indicator LCA results. The designs with high-performance scores and low environmental impact (indicated by the yellowish quarter in the plots in Fig. 6) can be recommended as the most optimal solutions.

Considering outdoor-appropriate layers, designs E5 (aluminium sheet) and E2 (fibre-cement board) can

Table 8.
Outer layers performance assessment

Layer No.	E1	E2	E3	E4	E5	E6	E7	I1	I2	I3	I4	I5	I6	I7
application	EW	EW	EW	EW	ER	ER	ER	ID	ID	IW	ID	IW	ID	IW
Fire resistance	1	2	1	1	2	1	1	1	2	0	1	1	2	1
Water resistance	1	1	1	1	2	2	2	1	0	1	0	1	0	1
Mechanic. resistance	2	2	1	1	2	2	2	1	1	0	0	0	1	1
Price and availability	0	0	1	0	1	1	1	1	0	2	2	0	2	0
Performance score	4	5	4	3	7	6	6	4	3	3	3	2	5	3

EW - exterior wall, ER - exterior roof, ID - indoor.

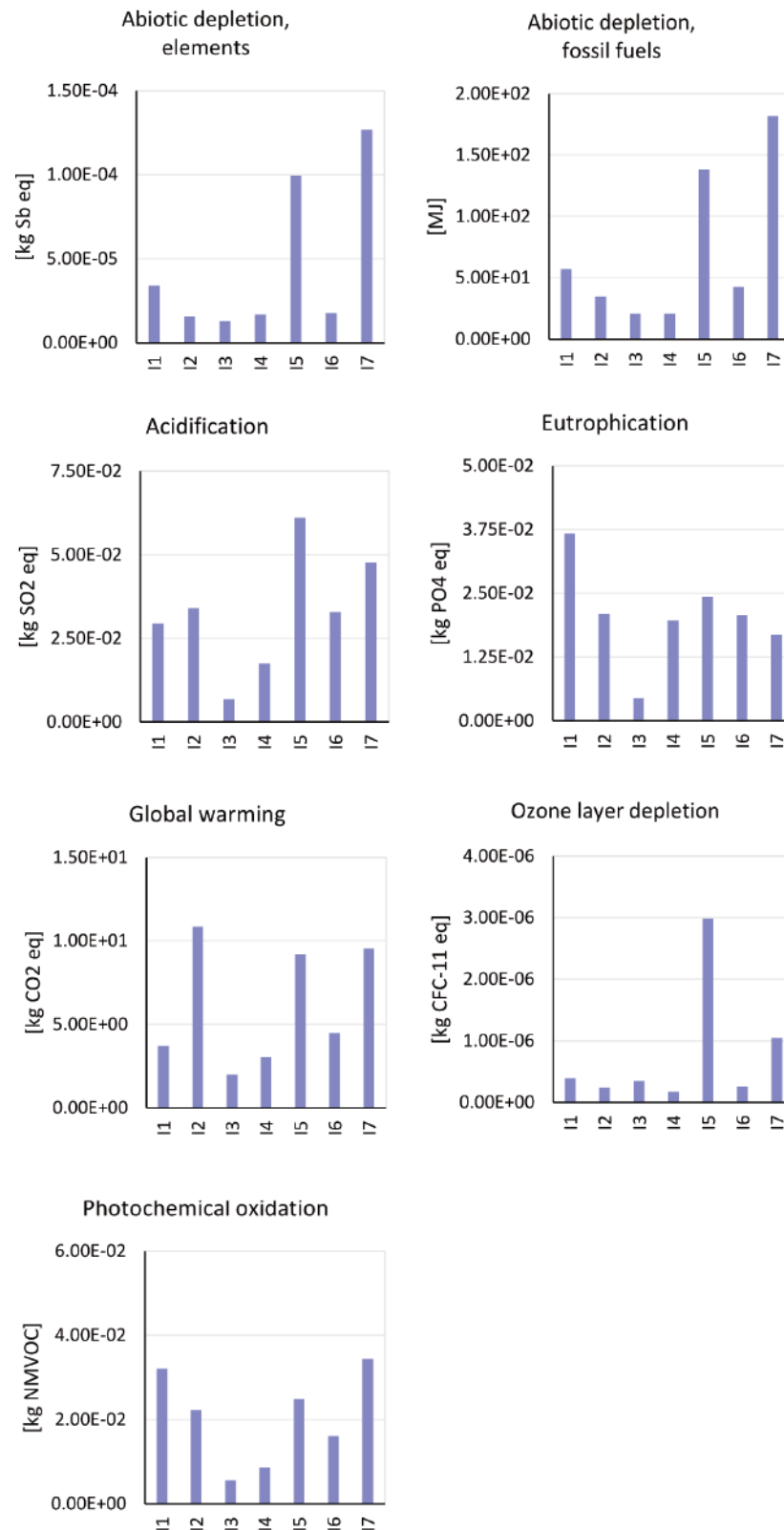


Figure 5.
Result of CLM 2001 method midpoint LCA analysis for interior layers I1-I7

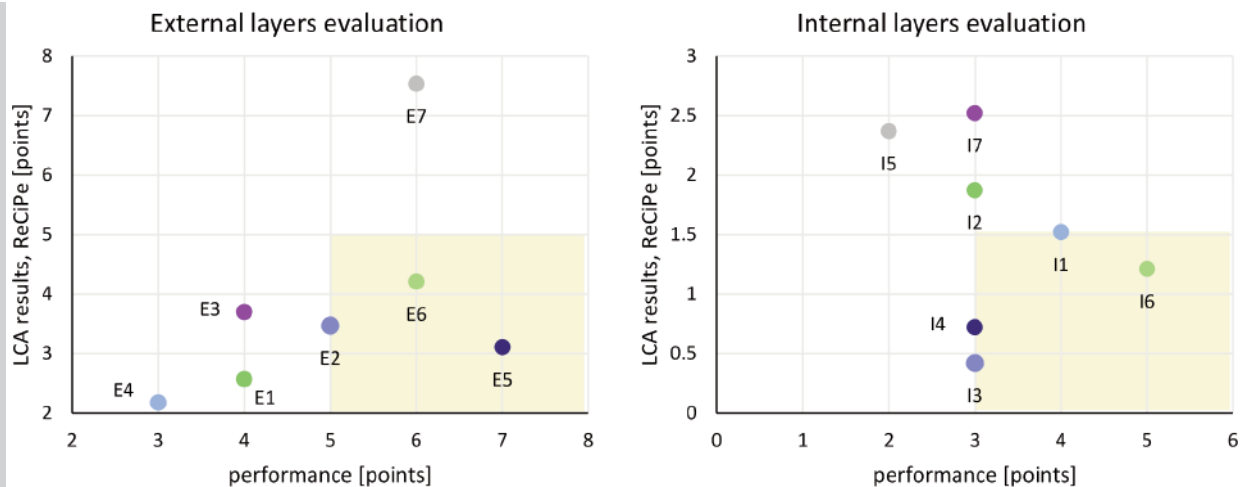


Figure 6.
Outer layers evaluation metric

be recommended. The E6 design also performed highly, however, the use of EDM membrane, which must be welded at high temperatures, raises questions about the safety and risk of spontaneous combustion of paper-based core that is meant to be protected. The choice of layers E1 (HPL) and E3 (plywood) may also be considered. In the case of indoor-only layers, design I6 (gypsum board) proved to be the most favourable. Nevertheless, variants I1 (plywood), I3 (PVC veneer) and I4 (fibreglass) should not be neglected.

The general performance and environmental burden are a good starting point for the selection of the outer layer for paper-based cores. However, for each application individual characteristics should be taken into account and factors such as type of paper-based core, type of building, life-span, assembly method, user requirements and local law regulations need to be considered. Some of the designs offer other benefits that have not been discussed in the presented analysis. For example, plywood or fibre-cement board may be used for aesthetic reasons, to showcase the beauty of the natural material, while painted variants (e.g. fibreglass) offer unlimited colour pallets. Furthermore, the use of heavy indoor layers, such as plywood, gypsum or MgO board, may noticeably increase the acoustic properties of lightweight partition walls, while lightweight proposals (e.g. fibreglass of PCV veneer) should be considered when low weight is a key factor, for example in temporary structures.

4. CONCLUSIONS

The conducted research analysed the performance, characteristics and environmental impact of fourteen design proposals of protective outer layers for paper-based envelopes. All the designs combine various materials and complementary coating techniques, in order to improve their performance. Depending on the materials, various mechanical, fire and water resistance were achieved, allowing for application to indoor and outdoor envelope surfaces. Apart from performance, the environmental impact should be a key factor in protective material selection, in order to maintain the ecological properties of paper-based envelopes. The presented LCA analysis forms the baseline for design selection, however, it should be noted, that each architectural scenario will require further analysis in these fields. Factors such as building type and lifespan, climatic conditions, materials availability and recycling possibilities should be considered. Moreover, further research regarding full envelopes (i.e. insulative core with both outer layers) should be conducted, to obtain more in depth knowledge regarding paper-based building envelopes.

FUNDING

This work was supported by the National Centre for Research and Development of Poland, under grant number Lider/60/0250/L-11/19/NCBR/2020. Agata Jasiołek was supported by the Foundation for Polish Science (FNP).

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