Wroclaw University of Science and Technology

DOCTORAL DISSERTATION

Paper-based building envelopes – design proposals and environmental assessment

by

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Background

This thesis was written within the interdisciplinary research project *Transportable Eco-friendly Cardboard House - R&D works on implementation of cellulose based materials in architecture*, led by Jerzy Łątka, who was also my assistant supervisor. The research team was formed of specialists in various disciplines, including architecture, civil engineering, acoustic engineering, building physics and chemistry. Although the thesis presents my individual work on paper-based envelopes, some interdisciplinary parts of the research were conducted in cooperation with other team members.

Several chapters and subchapters of the thesis have already been published in scientific journals, and others are undergoing the review process at the moment of the thesis submission. This information is always provided at the beginning of the chapter, followed by bibliographical references. Two of the subchapters (2.1 Paper as a building material and 4.1 Cores) were published as interdisciplinary articles co-authored with other members of the research team. Therefore, these subchapters include some sections researched or written by other team members. These parts are essential to the integrity of the work but *are included in summarised form*, containing only the information necessary to understand the rest of my research. To preserve transparency, *each co-authored section in indicated in the text of the thesis*.

Abstract

The thesis focuses on environmentally friendly lightweight building envelopes made of paper-based components. It aims to propose novel paper-based building envelopes, that will cause lower environmental impact than currently used alternatives, without compromising their performance. The following hypothesis has been formulated to meet the stated objective.

A full-performance building envelope with favourable environmental characteristics may be designed from paper-based components.

In order to confirm or reject the hypothesis, a five-phase research was conducted. Firstly, the State of the Art in paper as a building material and paper-based building envelopes was reviewed. Afterwards, research in three consecutive scales was conducted. In microscale laboratory tests on paper water protection, fire protection and lamination were conducted, to complete the existing knowledge gap. Next, six envelope cores and fourteen outer layers were proposed in mesoscale, followed by their environmental and performance assessment. Afterwards, two paper-based full-performance building envelopes were proposed in macroscale and compared to literature-based envelopes made of paper and non-paper materials. Finally, the selected paper-based envelope was implemented into the design of a housing unit prototype.

It was concluded, that aspects such as type of structure, amount of adhesive used, façade ventilation and protection against destructive factors have a significant impact on paper-based envelopes' environmental burden. However, as a result of the thesis it was proven, that replacement of conventional envelopes with paper-based ones, especially in buildings with a limited lifespan, may reduce their embedded environmental impact, as well as the amount of waste generated, due to the high recycling potential of paper.

Streszczenie

Rozprawa dotyczy proekologicznej obudowy budynku wykonanej z komponentów papierowych. Jej celem jest zaproponowanie nowatorskich projektów papierowej obudowy, generujących mniejszy wpływ na środowisko naturalne niż obecnie stosowane alternatywy, bez wpływu na ich właściwości użytkowych. Aby zrealizować postawiony cel, sformułowano następującą hipotezę.

Z komponentów papierowych można zaprojektować w pełni funkcjonalną obudowę budynku o korzystnych właściwościach środowiskowych.

W celu potwierdzenia lub odrzucenia hipotezy przeprowadzono pięcioetapowe badania. Najpierw dokonano przeglądu obecnego stanu wiedzy na temat papieru jako materiału budowlanego oraz papierowej obudowy budynku. Następnie przeprowadzono badania w trzech skalach. W mikroskali przeprowadzono badania laboratoryjne nad ochroną papieru przed wodą, ochroną przeciwogniową i laminacją, w celu uzupełnienia luk w stanie wiedzy. Następnie zaproponowano sześć rdzeni i czternaście warstw wykończeniowych w mesoskali, po czym przeprowadzono ocenę ich właściwości środowiskowych i użytkowych. W kolejnym etapie, makroskali, zaproponowano dwie papierowe, w pełni funkcjonalne obudowy budynku i porównano je ze znanymi z literatury odpowiednikami wykonanymi z papieru i innych materiałów. W ostatniej fazie badań wybrana papierowa obudowa została zaimplementowana w projekcie prototypowej jednostki mieszkalnej.

Stwierdzono, że takie aspekty takie jak rodzaj konstrukcji, ilość użytego kleju, wentylacja fasady i ochrona przed czynnikami niszczącymi mają znaczący wpływ na obciążenia środowiskowe generowane przez papierowe obudowy. Mimo, to, w toku rozprawy udowodniono, że zastąpienie konwencjonalnej obudowy budynku papierową, zwłaszcza w budynkach o ograniczonym okresie użytkowania, może zmniejszyć wpływ na środowisko naturalne generowany podczas ich produkcji, a także ilość powstałych odpadów, ze względu na wysoki potencjał recyklingowy papieru.

Contents

Chapter 1

Introduction

In 2020, over 37% of 2.153 billion tonnes of waste generated in Europe was caused by the construction industry [1]. The building sector is responsible for one-third of the world's greenhouse gas emissions [2] and 40% of energy consumption in Europe [3]. Moreover, building construction consumes approximately a quarter of materials extracted from the lithosphere all over the world [4]. In consequence, it is one of the most environmentally harmful, however essential, branches of the world's industry. The construction industry meets basic human needs by providing safety, privacy, comfort and a space for social interaction, thus the ecological change should be performed rather by reducing the environmental impact (EI) of production and building process, than by reducing the scale of production. These problems have also been addressed by legislation, including the European Parliament, that aimed for a 70% recycling rate of construction and demolition waste by 2020 [5]. United Nations 17 Sustainable Development Goals presents a wider perspective on sustainability, promoting also buildings safety, resilience, equality and inhabitants' health [6].

Building envelope is defined in this thesis as a lightweight, opaque building enclosure, dividing indoor and outdoor climate, and providing thermal, acoustic and visual comfort for occupants [7]. It also protects building and its occupants from water, radiation, dirt and microorganisms [8]. Lightweight envelopes are usually composed of three easily distinguishable layers – a thick core, providing thermal insulation and structural stability, with both surfaces protected with thin durable outer layers. Although envelope is one of the most crucial, yet complicated parts of the building [9], walls, in general, are responsible for the biggest EI among other building elements [10] and the whole building envelope is linked to nearly half of the energy embodied in the building [11]. A sustainable building envelope should address three main criteria: lifecycle evaluation (e.g. environmental, economic), occupants' comfort (e.g. thermal, acoustic) and social aspects (e.g. aesthetic values) [2]. These objectives are sometimes conflicting, for example, environmentally friendly solutions are often more expensive than conventional alternatives, hindering their wider-scale application. The introduction of low-impact yet affordable building envelopes is especially important in light of rising construction prices – in the third quarter of 2022, the construction cost of a new residential building in Europe increased by 10.6 % in comparison to the third quarter of 2021 [1].

One way forward in this area is to opt for new, sustainable building materials. Apart from traditional building materials such as timber [12], materials known from other areas of life may be applied in construction industry. One example can be paper, which combines availability, low price and favourable environmental performance. Paper is a common material known from products like books, printing papers, sanitary products and packaging materials. Due to the rising popularity of electronic media and devices, printing paper production has declined recently. Nevertheless, packaging paper production has developed, and it is the packaging industry that requires durability and resistance. New applications for paper products are arising as a result of developments in the paper industry. One of them is the use of these products as components of architectural structures, including building envelopes [13,14].

1.1. Motivation, hypothesis and goals

The following thesis aims to propose novel research-based building envelopes made from paper-based materials, that will cause lower environmental impact than currently used envelopes, without compromising their performance. Various prototypes constructed by designers and researchers all over the world have already proven the concept of paper-based envelopes, yet did not provide conclusive design guidelines. Although environmental qualities are considered the key advantage of paper, the environmental properties of the proposed designs were rarely assessed nor compared to conventional building envelopes. The presented dissertation aims to fill this knowledge gap. The following hypothesis has been formulated to meet the stated objective.

A full-performance building envelope with favourable environmental characteristics may be designed from paper-based components.

Structuring and expanding the knowledge of the properties of paper-based products and their use in architecture, with particular emphasis on building envelope, allows fot the formulation of knowledge-based design guidelines. The comparative assessment methods used will allow an objective evaluation of the relevance of the use of paper for the construction of the envelope in comparison to alternatives made of conventional materials, such as wood-based materials

Goals

In order to confirm or reject the hypothesis, eight specific goals were formulated. A graphical representation of goals may be found in Figure 1.1.

G1 Goal 1. To review the state of the art in paper-based products in architecture applications, summarise their characteristics and indicate knowledge gaps.

G2 Goal 2. To analyse and compare literature-based paper-based building envelopes.

G3 Goal 3. To develop water protection techniques for paper-based envelope elements that do not compromise the environmental properties of the material.

G4 Goal 4. To develop fire protection techniques for paper-based envelope elements that do not compromise the environmental properties of the material, and that can be combined with water-protecting impregnation.

G5 Goal 5. To develop paper lamination techniques that provide stable joints without significantly increasing the component's environmental impact or hindering the paper recycling process.

G6 Goal 6. To propose original designs of paper-based envelope cores, that provide structural stability, thermal insulation required by polish building code regulation and low environmental impact.

G7 Goal 7. To propose original designs of paper-based envelope outer layers, that provide protection against weather conditions, water, fire and mechanical damage, while maintaining low environmental impact.

G8 Goal 8. To assess the relevance of the proposed paper-based envelopes as a pro-ecological alternative to literature-based paper envelopes and envelopes made of conventional building material.

G9 Goal 9. To propose implementation of the selected paper-based envelope into a small-scale building.

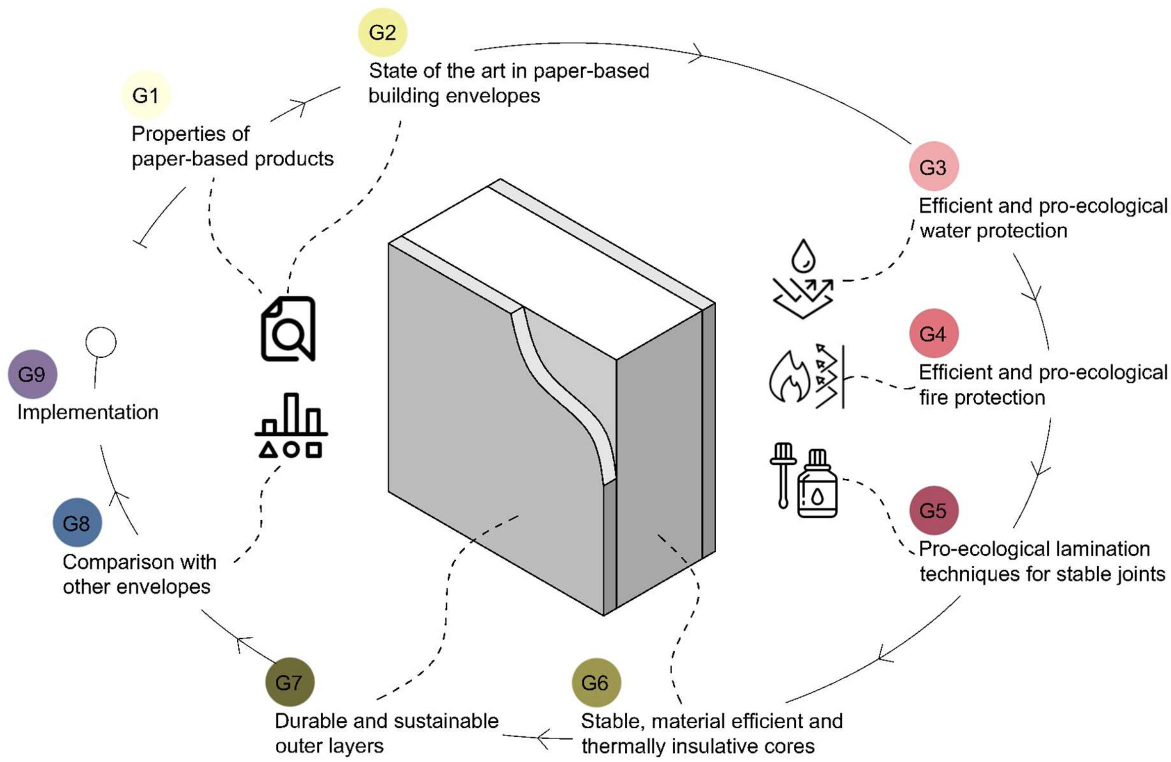

Figure 1.1. Thesis goals. [1]

1.2. Methodology and thesis structure

The conducted research was divided into five main phases, which are represented in this thesis by Chapters 2-6. Each phase builds on the results obtained in the previous one, leading to final envelope designs and evaluation. The first phase (Chapter 2) reviews the state of the art, stating the ground for the whole research. The following phases (Chapters 3-5) cover three different research scales – micro (small scale), meso (medium) and macro (big). The microscale aims at bridging knowledge gaps through water protection, fire protection and lamination research. Next, the mesoscale designs and analyses envelope cores and outer layers and finally, the macroscale assesses complete building envelopes. Such an approach allows for a gradual knowledge building and multi-criteria selection of optimal solutions. In the final phase (Chapter 6) a selected envelope design is implemented into a building.

Each of the research topics is represented by a subchapter that addresses one of the abovementioned research goals (G1-G9). In order to achieve the goals, specific research questions were formulated at the beginning of each subchapter. A large variety of research methods was used, depending on the research stage, including a literature search, case studies, laboratory tests

[1] All drawings, diagrams and photos by the author, unless stated otherwise in the footnote.

on small specimens, computer simulations, performance and environmental assessment. A summary of the thesis structure and applied methods used is presented in Figure 1.2. Detailed methodology descriptions are provided at the beginning of each subchapter.

	PHASE	INPUT	RESEARCH METHODS	STANDARDS	OUTPUT
STATE OF THE ART	2.1. PAPER IN ARCHI-TECTURE G1	previous researches regarding paper in architecture	• literature search (Web of Science, Google Scholar, Scopus, ResearchGate)	not applicable	paper-based products characteristics, knowledge gaps
	2.2. PAPER BUILDING ENVELOPES G2	previous researches, case studies and prototypes of paper-based envelopes	• literature search (Web of Science, Google Scholar, Scopus, ResearchGate)	not applicable	paper-based products characteristics, typology and comparison
MICROSCALE	3.1. WATER PROTECTION G3	• state of the art (impregnation research) • market offer of water impregnates	• test of water absorption in partial immersion • test of water vapor absorption in high humidity conditions	• ISO 29,767 • ISO 2812-2 • ISO 5637 (modified)	efficient water protection techniques for paper
	3.2. FIRE PROTECTION G4	• state of the art (impregnation research) • market offer of fire retardants	• single-flame source ignition test • charred areas analyses • long-term specimens observation	• ISO 11925-2	efficient fire protection techniques for paper, combination with water protection
	3.3. LAMINATION G5	• state of the art (lamination research) • market offer of adhesives	• single-lap tensile test • adhesive assessment - Ease of Handling Score	• ISO 4587	efficient lamination techniques - type and amount of adhesive
MESOSCALE	4.1. CORES G6	• state of the art (thermal properties) • lamination research	• heat flux numerical simulation in ThermCAD software • comparative Life Cycle Assessment - CLM midpoint and ReCiPe endpoint methods	• ISO 6946: 2017-10 • ISO 14040 • ISO 14044 • EN 15804	six insulative paper-based cores with environmental assessment
	4.2. OUTER LAYERS G7	• water protection • fire protection • lamination research	• comparative Life Cycle Assessment - CLM midpoint and ReCiPe endpoint methods • performance assessment - Performance Score	• ISO 14040 • ISO 14044 • EN 15804	fourteen envelope outer layers with environmental and performance assessment
MACROSCALE	5. BUILDING ENVELOPES G8	• cores research • outer layers research	• comparative Life Cycle Assessment - CLM midpoint and ReCiPe endpoint methods • performance assessment - Performance Score	• ISO 14040 • ISO 14044 • EN 15804	two full performance, pro-ecological paper-based building envelopes
IMPLEMENTATION	6. BUILDING G9	• envelope research	• prototyping • architectural design	not applicable	housing unit design with paper-based building envelope proposal

Figure 1.2. Scheme of thesis structure and methods used.

Chapter 2

State of the art

This chapter reviews the state of the art in architectural application of paper-based products, current as of the beginning of 2023. Over 160 references have been chosen for this review, resulting in a comprehensive, multi-disciplinary survey. Mechanical, thermal, acoustic and environmental properties of paper-based products were described, as well as lamination and protection techniques. In the second part of the chapter ten literature-based paper building envelopes are described and compared. The state of the art allowed for knowledge gaps indication and serve as an input to further stages of the research.

2.1. Paper as building material [2]

Despite the fact that paper production was subjected to large technological development through centuries (especially in the 20th and 21st centuries) paper still remains a simple, low-tech material whose main mechanical properties depend on bonds between the cellulose fibres. Cellulose is the main structural fibre in the plant kingdom. It is the most common natural polymer on the planet, and its resources are considered almost inexhaustible [15]. The extraction of cellulose in its fibrous character is the key process of pulp production. The paper production process consists of mixing pulp with water and pouring it onto the screens. This slurry consists of 99.7% water. Most of the fibres are aligned in the direction of the screen's movement (machine direction), which determines the anisotropic character of the material. Then the water is drained and the pulp is pressed and dried. During that process, hydrogen bonds are created between cellulose fibres. The connections between the fibres determine the mechanical properties of the material. Longer, slender, and more flexible fibres create stronger paper. Thus, an optimal raw material for strong paper is coniferous trees [16,17]. There are several methods to obtain paper pulp. Among them, the chemical sulphate (Kraft) method results in the cleanest pulp consisting of approximately 95% cellulose, which is suitable for strong papers [18]

Pulp can be obtained from any plant cell; therefore, the resources of fibres have a large variety. Fibres can have a wood or non-wood origin or can be obtained from recycled materials. The most common resource for pulpwood is hardwood (eucalyptus, aspen, birch, acacia, maple, oak, beech, balsam), softwood (spruce, fir, pine, cypress, hemlock, larch) and timber residues (sawmill chips and sawdust) [19,20]. Non-wood pulp is obtained from agriculture residues (sugarcane bagasse, linen and flax seeds, corn stalks, cotton stalks, wheat straw, rice straw, banana stem), natural growing plants (bamboo, esparto, reeds, paper mulberry, sabia grass, elephant grass, switch grass,

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[2] Research from this subchapter has been published as a scientific article in Journal of Building Engineering [14], together with Jerzy Łątka, Anna Karolak, Paweł Niewiadomski, Paweł Noszczyk, Aleksandra Klimek, Sonia Zielińska, Szymon Misiurka and Dominika Jezierska.

papyrus), non-wood crops (cotton linters, cotton rags, Jute, ramie, sunn hemp, hemp, kenaf, palm), and textile waste [20,21]. The resources for recycled paper are preconsumer (wastes generated in papermaking mills), and postconsumer (paper, cardboard and fibrous material collected from the packaging industry, retail stores, offices and households, such as printing papers, magazine waste, newsprint waste, corrugated cardboard, shredded currency waste, cotton rags, or even rhino, cow or elephant dungs) [20,22]. Paper can be recycled up to seven times, however each time during the recycling process, fibres are subjected to mechanical processes which result in the decreasing of their mechanical properties [23].

There are many different products manufactured by the paper industry. Next to the typical ones known from everyday life such as sheets of printing paper, newspaper or hygienic papers, several products have properties that make them suitable for application in architectural structures. These are paperboard, corrugated cardboard, honeycomb panels, and paper tubes [24].

There is common confusion about the notion of paper and cardboard. Usually paper refers to thin paper products, while cardboard refers to thicker ones. According to the ISO 4046 1-5 standard from 1978, the grammage of paper is lower than 224 g/m^2. Above that, we can talk about cardboard, and in the case of multi-layered products, this threshold is set at 160 g/m^2. However, both products are the same according to their material composition.

Paperboard is a generic name assigned to the different types of paper with relatively high rigidity such as carton, solid board, or solid fibreboard (see Figure 2.2a). Paperboard is produced as a homogeneous material or a composition of several laminated layers, and it can be finished with some special layer, i.e. waterproof polyethene resin. Paperboards can be used for the production of food packaging such as folding cartons or paper cups. Its thickness ranges from 0.25mm to 4mm and its weight ranges from 224 g/m^2 to 1650 g/m^2.

Corrugated cardboard is a multilayer material composed of at least one liner and one corrugated medium, a flute (see Figure 2.2b). The thickness of the fluting ranges from 0.8 to 4.8 mm and its grammage from 80 to 180 g/m^2. The grammage of the liners varies from 115 to 350 g/m^2 [25] There are several types of corrugated cardboard determined by the number of layers of the flute (from single to triple wall) or by the height of the fluting. The smallest fluting G has less than 0,55 mm, while the largest A has a height between 4.0 and 4.9 mm. There is an extra-large flute K, which is higher than 5.0 mm. The most typical flute sizes are presented in Figure 2.1. Corrugated cardboard is mainly used for packaging since its sandwich structure provides a relatively high rigidity with a low amount of material.

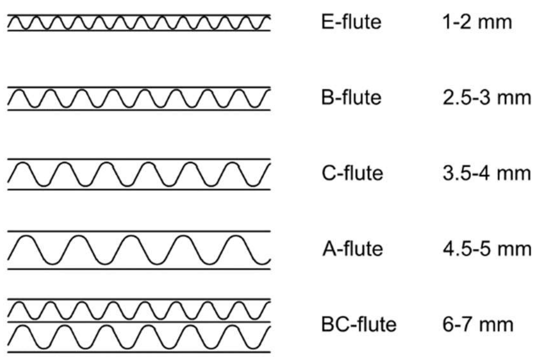

Figure 2.1. Most popular corrugated cardboard flute sizes and their thicknesses.

Paper tubes (or paper cores) are special paper products used for the transportation of paper, textiles, or other materials, or in the building industry in the case of larger tubes (see Figure 2.2c). In general, the diameter of paper tubes varies from 5 mm for drinking straws to 1600 mm for tubes used as disposable formwork [26]. There are two ways of producing paper tubes: parallel winding and spiral winding. Parallel winding consists of subsequent layers of paper that are winded on the inner core and glued together. In this method, the length of the tube is determined by the width of the paper. In the spiral method, the paper stripes are fed at a certain angle. During production, a tube slides off the core while new layers of paper are fed and glued. This method is endless, and it depends on the size of the production plant or transportation limits. The parallel-winded paper tubes are stronger and easier for mechanical calculations as the main direction of the cellulose fibres in the material (machine direction) coincides with the axis of the tubes. However, due to production constraints, spiral-winded tubes are mostly used as structural elements in architecture.

Honeycomb panels are low-density cellular sandwich panels. They are made up of three layers: two facings and an inner honeycomb-shaped core in the middle (see Figure 2.2d). The production of honeycomb panels is divided into two steps. The core is produced by linear lamination of the stack of paper sheets, which is then cut into slices. The thickness of the slice determines the height of the panel. The slice is pulled apart and stretched, and thus honeycomb-like cells are created. Then, the top and bottom faces are glued to the core. The height of the panels varies from 8 to 100 mm, with a popular thicknesses of 10, 12.5, 25 and 50 mm [27]. The common cell sizes of internal honeycomb layer are 8, 10, 14 and 22 mm. Smaller cells implies higher mechanical strength, but also higher weight of the element.

Figure 2.2. Paper-based products for architectural applications; (a) paperboard (on the example of paper L-shape; (b) corrugated cardboard panel; (c) paper tube; (d) honeycomb panel.

Depending on the properties and composition of the material, some of the aforementioned materials have a greater potential to be used as linear structural elements such as pillars and beams, while others are used as planar elements. Some of them can be transformed and used as both linear and planar elements.

2.1.1. Paper in architectural applications

Since its invention, the paper has gained increasing reliability and has been implemented in many fields of everyday human activities. The history of paper development shows how paper products were used from small objects in ancient times to large-span structures today.

Initially, paper was used to share religious ideas, whether it was in China, the Islamic world, or Europe. Later it was incorporated as a general medium for written communication i.e. books and scrolls and dissemination of information, as well as for official documents, agreements and money. In China, paper was used in burial ceremonies as a representation of material goods. As everyday commodities, paper was used mainly for wrapping, but also as toilet paper, tea bags, or playing cards [28–31].

The first examples of the use of paper in architectural applications had a form of folding screens produced in China and Korea. The oldest references to such a product are from the eighth century A.D. [32]. Another application had the form of sliding walls and room dividers. These were exceptionally developed in Japan. Fusuma panels, which were opaque and often covered with paintings, and shoji panels that allow light to pass through are typical elements of traditional Japanese architecture (see Figure 2.3) [33].

Figure 2.3. Japanese traditional paper screens; (a) folding screen, contemporary production with traditional techniques, Kyoto, 2013; (b) shoji (translucent paper screens) and fusuma (sliding panels) in Nazen-ji temple, Kyoto 2013 [3].

Apart from traditional far east applications of paper as a building material, experiments appeared together with the creation and mass production of new paper products [24]. The first approach of paper products use in architectural structures in the Western world reached the second half of the nineteenth century. French company ADT created in 1867 a series of prefabricated buildings that included summer houses, hospitals, and houses for tropical countries. All of these structures were produced with the use of paperboard panels that make up walls with air cavities inside [34].

The high uptake of paper products in the building industry was related to the housing shortage after the Second World War, especially in Europe and the United States. The experiments conducted in the next four decades by both universities and private companies resulted in a series of structures in which paper-based products were employed together with other materials. Mostly, paper board and honeycomb cardboard panels were used as elements of composite structural panels [35].

The Experimental Shelter developed by the Institute of Paper Chemistry from the USA in 1944 consisted of paperboard elements formed in the 25 mm thick corrugated plates soaked in sulphur and coated with fire retardant. The life span of the structure was assumed to be one year; however, some of them were in use even for 25 years [34,36]. The Container Corporation of America in

[3] Photos by J. Łątka.

Chicago created in 1945 a dome-like shelter made of plastic coated paperboard panels mounted with staples [34].

An interesting example, created by Herbert Yates and developed by Sanform Hirsen and Sym van der Ryn in 1966 was Plydome - a shelter for seasonal workers. The structure was made of 10 mm thick paperboard panels filled with polyurethane foam and waterproofed with a polyethene film from the outside. The panels were transported as a flat package and unfolded on site along the parallel valley and mountain folds. Two panels were connected to each other, enclosed with end walls, and anchored to the floor chipboard plate. That gave the rigid, A-like section house with dimensions of 5.15 x 5.80 and 3 m height [34,36,37].

For the occasion of the Olympics in Munich in 1972, 3H Design company created the idea of Pappedern, an 11.5 m^2 unit that could serve as service rooms, recreation, kitchenette, lavatory, cloakroom or storage. Units had a form of bevelled cubes and were made up of 30 mm thick corrugated cardboard coated with fibreglass. The Pappedern units were prefabricated and delivered to the site in one piece. They could be independent or combined into groups. 89 Paperderns were used during the Olympics [34,38]. A few years later, for his graduation project at TU Eindhoven, the Dutch architect Paul Rohlfs designed a concept of a paper house made of honeycomb panels. After graduation in 1975, Rohlfs continued to work on the idea of paper houses and built several prototypes. Prototype No. 4 was composed of honeycomb panels with an exterior breather foil and an interior vapour barrier. It was inhabited for several months [39].

The long tradition of the use of paper in architecture in Japan was developed nowadays by the Japanese architect Shigeru Ban. This winner of a Pritzker Price award is famous for incorporating in his project paper tubes as structural elements. For the first time, he reached for paper tubes in 1986, when he was searching for a cheaper alternative to timber when preparing an exhibition of architect Alvar Aalto. Since then, Shigeru Ban has developed the potential of the use of paper-based products in architectural application. His projects have initiated a new era of paper-based products in architecture followed by contemporary research in that area [35]. The first permanent paper tube structure made by Shigeru Ban was an extension of the house in the form of a self-standing library. The Library of a Poet was composed of six paper tube truss supports covered with an arched roof of paper tubes. Created by Shigeru Ban in 1995, Paper House is recognized as the first fully operating house with permanent permission where paper-based products were incorporated as main structural elements. The house is composed of paper tubes walls forming an S-like pattern, which functionally divides the house space.

In the same year after a severe earthquake in Kobe, Japan, Shigeru Ban had founded the Architects' Voluntary Network, the NGO that deals with humanitarian architecture [40,41]. One of the first emergency shelters designed by Ban was the Paper Log House (see Figure 2.4a). The small unit enclosed the space of 16 m^2 and was composed of beer crates filled with sandbags as foundations, timber floor, paper tube walls and PVC textile roof stretched on paper tube truss. The walls were made of a series of paper tubes placed next to each other and connected by means of steel rods.

The largest structure where paper products were used as structural elements was the Japan Pavilion at the Expo in Hannover in 2000 (see Figure 2.4b). Design by Shigeru Ban in cooperation with Frei Otto, the pavilion was a double-curved surface with the dimensions of 74 m long, 25 m wide, and 16 m high. The pavilion was a three-dimensional one-meter grid shell composed of 440 paper tubes. The tubes overlapped themselves and were connected to each other with elastic bands to allow three-dimensional movement and rotation during the construction process. The paper tube grid shell was enhanced with laminated timber arcs and purlins that run alongside the pavilion. The whole structure was covered with a membrane composed of flameproof polyethene, non-combustible paper, glass fibre fabric, and PVC.

So far, Shigeru Ban has created 65 projects where paper tubes were employed as a main structural material. Those projects vary from industrial design objects (Chair from Carta Series), emergency architecture (Paper Log House Series 1995 – 2014, Paper Partition System 2004 - 2020, Paper Nursery School 2013), temporary pavilions (Paper theatre 2003, Camper Travelling Pavilion 2011), university buildings (Paper Studio 2003, Shigeru Ban Studio at KUAD 2013 – see Figure 2.5b), Churches (Paper Church 1995, Cardboard Cathedral Christchurch 2013), to permanent buildings (Paper House 1995, Full House 2020). Next to the tubes, Shigeru Ban also experimented with honeycomb cardboard boards in such projects as Nemunoki Children Art Museum 1999, or with gable walls of Japan Pavilion in Hannover 2000 [42–44].

Apart from Japanese experiences, there were several paper-based realizations in the Western World. The Westborough Primary School designed by Cottrel & Vermeulen Architecture in cooperation with Buro Happold consulting engineers was a structure that received building permission in 2001, as first in Europe (see Figure 2.5a). The goal was to erect a structure that could be used for at least 20 years. This 90 m^2 building functions as a social space for kids. The structure consists of several paper-based elements. Two walls composed of 11 paper tubes each hold the timber roof truss; another 7 paper tubes placed in a row take the load from the roof on the side where the big opening with folding walls is placed. The wall and roof panels are made of sandwich panels composed of paperboard and honeycomb panels fitted into the timber frame.

Additionally, for protection purposes, the walls are covered from the outside with cement fibreboard panels. The aim of the project was to create a building that would be made of 90% by volume from recyclable materials. However, due to the legal restrictions and results from research and prototyping, finally only 29% were made of paper-based elements. The example of Westborough Primary School shows that the primary assumptions need to be corrected by real-scale objects, sometimes to a large extent. The building at the moment (spring 2023) is still in use[45–47].

Figure 2.4. Examples of the architecture of Shigeru Ban with paper tubes; (a) Paper Log House; (b) Japan Museum [4].

Figure 2.5. Examples of modern paper-based architecture; (a) Westborough Primary School; (b) Ban's studio at Kyoto University of Art and Design [5].

[4] Photo (a) and by J. Łątka; (b) by M. Brzezicki.

[5] Photos (a) by B. Vermeulen; and (b) by J. Łątka.

The other European example of a permanent structure where paper tubes were employed is a social room of Ring Pass Hockey Club in Delft, the Netherlands. The 128 m^2 building designed and built by Octatube has a roof structure made of a spaceframe of paper tubes (see Figure 2.6a). The tubes were connected to each other by means of 'tuballs' specially designed metal casted connectors, which used threaded rods to pre-stress the tubes. Due to this solution, paper tubes were not perforated and therefore weakened and exposed to the influence of humidity in order to be connected to joints. As the structure was part of the research, the tubes were treated three times. Some of them were coated with varnish, some were covered with polyethene hit-shrinkable sleeves, and some were left without any protection. The building is being monitored and has been in use for 11 years [24].

A building where corrugated cardboard was used as the main structural material is a Dutch prefab Wikkelhouse (see Figure 2.6b). The building segments are produced by wrapping subsequent layers of corrugated cardboard on a house-shaped mould with dimensions of 3,4 x 2,4 x 1,2 m. This segment is composed of 24 layers of glued corrugated cardboard, protected from the inside with a plywood layer, and from the outside with watertight and breathable textile covered with timber planks. Pre-fabricated segments with a usable area of 5 m^2 are transported to the desired location, placed on the foundation, combined and caped with gable walls. Despite the fact that Wikkelhuse is made of corrugated cardboard, the producers – Fiction Factory - give a 20-year guarantee on the assumed 50-year lifespan of the object [24,45].

Figure 2.6. Examples of modern paper-based architecture; (a) Ring Pass Hockey Club; (b) Wikkelhouse [6].

Each time on the occasion of design, development, and construction of paper architecture, there is research conducted by universities or consulting companies. Research on some of the Shigeru

[6] Photos by J. Łątka.

Ban projects is widely described by McQuid [42], the Westborough Primary School development process was reported by Andrew Cripps of Budo Happold [46–48], and the Ring Pass Hockey Club was designed on the basis of previous research conducted at Technical University in Delft within the “Cardboard Architecture” group [39]. However, there were also physical outcomes in form of prototypes and projects as a result of the research itself. The research group at Wroclaw University of Science and Technology (WUST) focuses on the potentials of the use of paper-based elements in temporary structures, housing, and emergency architecture. Transportable Emergency Cardboard House version 3 (see Figure 2.7a) and 4 (see Figure 2.7b) are the results of the research project carried out at WUST [24,49]. The Cardboard in Architectural Technology and Structural Engineering (CATSE) was a collaborative research platform operating at ETH Zurich in the years 2003 – 2009. The results of the research were two dissertations on corrugated honeycomb panels as potential material for the building industry [50–52]. The largest research group has been operating at the Technical University in Darmstadt. The BAMP! (Bauen mi Papier – Building with Paper) project involved 16 PhD students from different departments such as architecture, chemistry, mechanical engineering, building and environmental science. One of the results of the group effort was a full-performance paper house prototype presented in Figure 2.7c [53].

Figure 2.7. Examples of paper-based emergency architecture; (a) TECH 03, (b) TECH 04, (c) Full performance paper house [7].

It can be seen that contemporary projects where paper-based products are employed as structural elements vary in used materials, structural system, function, size, and lifespan. It is more the designers who adapt to the offer of the paper industry and try to incorporate already existing products than the fundamental material research that results in testing prototypes. This approach

[7] Photo (a) by J. Łątka; (c) from [50].

results in gaps in the thorough knowledge of materials including details of building mechanics, thermal insulation, acoustics, gluing, and impregnation methods, which have an impact on the eco-friendly properties of the material.

2.1.2. Mechanical properties of paper-based products [8]

From the mechanical point of view, paper and cardboard (and other paper materials and products) are in general inhomogeneous, anisotropic materials characterized by non-linear, visco-elastic-plastic behaviour [54]. They are also hygroscopic materials [24]. Mechanical properties strongly depend on the type of paper products (types of fibres binder) and their structure (fibre orientation, like in the case of wood and the production process) and hence density, as well as many other factors, such as moisture, time of loading, etc. [55]. According to the literature, i.e. [56] the effect of moisture is significant, while the effect of temperature is relatively small.

Researchers dealing with the issue of determining the mechanical properties of paper and paper products often distinguish, identify, and describe three basic directions related to the production process: machine direction (MD), cross-machine direction (CD), and thickness direction (ZD) [56]. The described directions of paper are presented in Figure 2.8.

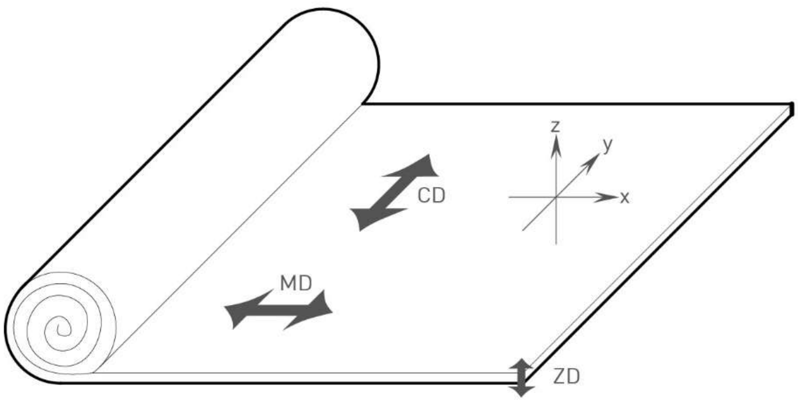

Figure 2.8. Directions of paper: machine direction (MD), cross-machine direction (CD) and thickness direction (ZD) according to [56]. [9]

[8] Research from this section was conducted by Anna Karolak and Paweł Niewiadomski.

[9] Drawing by D. Jezierska.

Mechanical behaviour of paper

As studies and analyses by Felleres show, the paper has better parameters in tension than in compression [57]. The comparison of static behaviour in tension and compression for the machine direction and the cross-machine direction (typical stress-strain curves) of the paperboard described in [57] is presented in Figure 2.9.

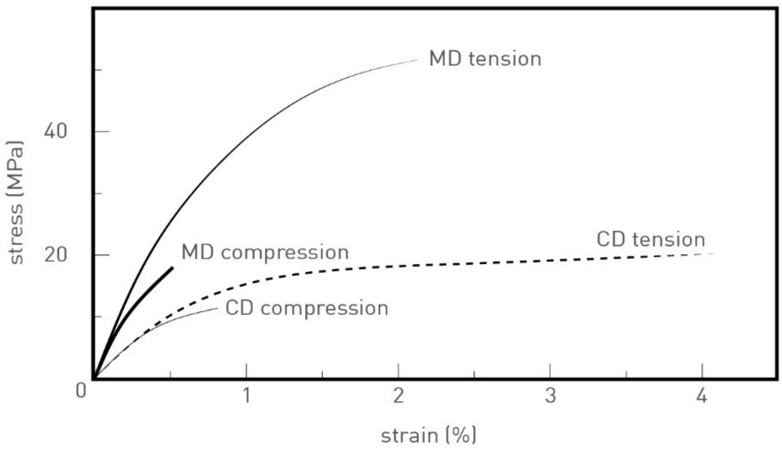

Figure 2.9. Static behaviour of paperboard in tension and compression according to [57]. [10]

Analysing the graph, it can be seen that for machine direction (MD) and cross-machine direction (CD), paper failure occurs sooner under the compressive stress than the tensile stress. In turn, in the thickness direction (ZD) the situation is the opposite [56]. The four different plots that are visible in the graph also indicate the anisotropy of the material. Moreover, it can be noticed that the MD paper is stronger than the CD. In MD it is stiffer, the strength is higher, and the deformation is lower. Furthermore, the static behaviour described by the graph plots presents mainly a brittle failure (except for the curve for the cross-machine direction tension). In the case of brittle failure, no significant plastic deformation occurs prior to actual failure. As can be seen in the graph, the range corresponding to the nonlinear behaviour is relatively small.

The anisotropy of paper and paper-based products is a consequence of the production process. During the forming process, the fibres are aligned in the machine direction (MD) more than in the cross-machine direction (CD). As a result, paper or paperboard is stronger in the machine direction than in the cross-machine direction. The anisotropy – ratio of parameters in the machine direction and cross-machine direction also depends on the properties of fibre itself and clearly are

[10] Drawing by D. Jezierska.

related to the manufacturing process, and hence it is difficult to point the constant values. Nevertheless, the literature [58,59] presents the general relations of the mechanical properties of paperboard. They are presented in Table 2.1.

Table 2.1. General relations of the mechanical properties of paperboard according to [52].

Parameter/ direction	Machine direction (MD)	Cross-machine direction (CD)
E [GPa]	2 – 20	1/4 – 2/3 E_{MD}
σ_t [MPa]	15 – 45	1/3 – 1/2 $\sigma_{t, MD}$
σ_c [MPa]	1/3 $\sigma_{t, MD}$	1/2 $\sigma_{c, MD}$
ε_t [%]	1.5 – 2.5	3.0 – 4.0
ν	0.4	0.1
G [GPa]	1/3 ($E_{MD}E_{CD}$)	½ ($E_{MD}E_{CD}$)

Analysing the data presented in the table above, it can be concluded that most of the mechanical parameters of the material can be estimated based on a single test - the tensile test, in the case where there are no more experimental data available. However, the relations collected in the table are still general and rather illustrative than accurate. It should be remembered that the data are related strictly to the particular paper type; therefore, it is recommended to conduct the full testing program that will allow obtaining accurate information. It only confirms the lack of information needed to fully describe the static behaviour and determine the mechanical parameters of paper and paper products under different load cases.

There are also many examples in the literature that present case studies, examples of building small paper or cardboard structures with a description of experiences and recommendations. The authors often do not refer to specific values of mechanical parameters, stating in general that the material can be properly used as a construction material. Such examples were presented in the previous sections. There are also works with the detailed test descriptions and obtained values from experimental investigations on paper and paper products. Some of them are presented below. Unfortunately, the literature does not necessarily provide information on the exact dimensions of the described paper product and the type of material used. It should be remembered that these properties may have a significant impact on the values of the parameters presented.

Mechanical properties of paper-based products

Schönwälder et al., i.e., in [58] present some mechanical parameters of different paper products, such as paper tubes (cardboard tubes) and honeycomb panels (honeycomb sheets) that may be used to design elements and constructions with the application of this material. The tensile strength and compressive strength of the tubes were estimated at approximately 8 MPa, while the long-term tensile strength and compressive strength affected by the creep effect were several times lower – about 1-2 MPa. The modulus of elasticity E for the paper tubes was about 1-1.5 GPa. In turn, for the 20 mm thick honeycomb panels, the recommended bending strength value was 6.9 MPa. The design tensile and compressive strengths considering the creep effect were more than ten times lower, 0.6 MPa. The modulus of elasticity E for this material was about 1 GPa.

Correa in [60] analysed the use of paper tubes with thick walls for design. He used the data from the experimental tests performed by Block in Japan and Germany described in [61]. The values of the modulus of elasticity, allowable compression stress, and allowable bending stress (both under short-term and long-term loading) are presented. The modulus of elasticity for paper tubes under short-term loading is equal to 1 to 1.5 GPa and under long-term loading about 1 GPa. The allowable compression stress under short-term loading is 4.4 MPa and the allowable bending stress under short-term loading is 6.6 MPa. The values of these parameters are twice as low in the case of long-term loading. Moreover, some more general conclusions can be drawn from the tests conducted on the properties of paper tubes [61] and presented in the paper [60]. They are as follows: the material stiffness is about 1/5 of softwood, it is very sensitive to the duration of loading and to variations in moisture content (up to about 7%, while after this level, the strength value decreases about 10% for every 1% increase), it has a significant rate of creep (the phenomenon occurs already at 10% of the failure loading), and the bending strength is generally 50% greater than the compression strength.

Bank et al. presented a comprehensive overview of the paper tube manufacturing process, material properties, structural applications, design, and approaches in [26]. The work demonstrated that highly engineered paper tubes can be successfully applied in large structures, which can endure in the outdoor environment even 20 years or more. The authors present mechanical parameters of paper tubes established by static testing – axial compression and bending, used in different projects (i.e. Library of Poet, Paper House, Paper Dome and Japan Expo Pavilion 2000). The tubes analysed had different dimensions: diameters from 75 to 220 mm and wall thicknesses from 10 to 30 mm and were tested at different moisture content levels, 7 to 10%. The compressive strength was about 5-10 MPa, the modulus of elasticity in compression was about 1-2 GPa. In turn, the bending strength was approximately 8-16 MPa and the modulus of elasticity in the bending was 1.5-2 GPa. The same authors in [62] and [63] present more results of the modulus of elasticity in bending of paper tubes from dynamic modal testing. The values obtained from this parameter ranged from 1.7 to 4.2 GPa for tubes with different diameters and wall thicknesses.

Pohl et al. [51,52] tested corrugated paper honeycomb, among other things, in terms of mechanical parameters. They performed compression tests to determine the out-of-plane compressive modulus and compressive strength, long-term compression tests, shearing tests to determine the out-of-plane shear modulus, shear strength, and long-term shearing test. In the case of compression tests, the authors established the material exhibited linear load-displacement behaviour up to at least 50% of the failure load. The results of the experiments were as follows: out-of-plane compressive strength – 1.4 MPa, out-of-plane compressive modulus – 0.2 GPa, shear strength in a weak and strong direction, respectively – 0.4-0.8 MPa and shear modulus in a weak and strong direction, respectively – 0.04-0.09 GPa. Furthermore, the authors compare the results with the values of the responding parameters of hexagonal paper honeycomb, described i.a. in. [64–66]. As the comparative analysis shows, the corrugated paper honeycomb seems to have similar strength and shear moduli as the typical hexagonal paper honeycomb with a density of 20-50 kg/m^3. In contrast, the out-of-plane compressive strength of the corrugated paper honeycomb was higher, which may be related to the higher density. Thus, the material seems to be suitable for application in sandwich elements, where impact loads are expected. Of course, as the authors point out, for use in structural elements, the paper honeycomb must be impregnated against the environmental humidity and the permanent stress level must be kept low, as the material is sensitive to these factors.

In her work [50] Ayan analysed the mechanical behaviour of corrugated paper honeycomb core sandwich composites. In the compression tests the component with 52 mm core thickness and 1,5 mm of steel facing achieved an axial load of 66 kN. In addition, improvements against moisture-humidity penetration were tested. It turned out that the maximum comprehensive strength of an impregnated material, when wet, is tested to be 1.24 MPa, around the same value of an unimpregnated material. However, the impregnation was effective when thermal conductivity was considered.

Pflug et al. [27] tested folded honeycomb cardboard for structural applications. The authors analysed the structural behaviour under compression for different types of cardboard. After a series of tests, they stated that the tested material has good mechanical properties and could find application in structural use.

Also, Heyden et al. [67] conducted an assessment of the utilization of corrugated cardboard as the core material for sandwich panels. They conducted compression and tension tests according to the standards EN 14509 and EN 789, describing testing methods for wood-based panels and faced panels. The compressive and tensile strength, as well as the modulus of elasticity in axial compression and axial tension, were determined. The authors also performed shear tests according to the standard DIN 53294 for testing sandwiches under shear loading, and the shear strength and the shear modulus were determined. Moreover, four-point bending tests according to DIN EN ISO 6892-1 were conducted on sandwich beams, which allowed us to establish the material structural behaviour under flexural loading. The influence of humidity on the values of the obtained parameters was also examined. As demonstrated in the test results, the material strength and stiffness parameters are significantly dependent on the direction of the load and the level of humidity. What the authors underline is that the material has similar or higher strength and stiffness in comparison with commonly used core materials such as mineral wool or polyurethane foam. In conclusion, it is stated that the use of corrugated cardboard as an alternative core material for sandwich panels is appropriate from a structural point of view. Nevertheless, the authors recommend continuing testing of the material, both for its long-term behaviour and in terms of other applications.

Taking into account the above, paper and paper-based materials appear to be promising construction materials in terms of their mechanical properties. Table 2.2 and Figure 2.10 present the approximate values of the mechanical parameters of the paper and the paperboard in comparison with the parameters of other commonly used building materials.

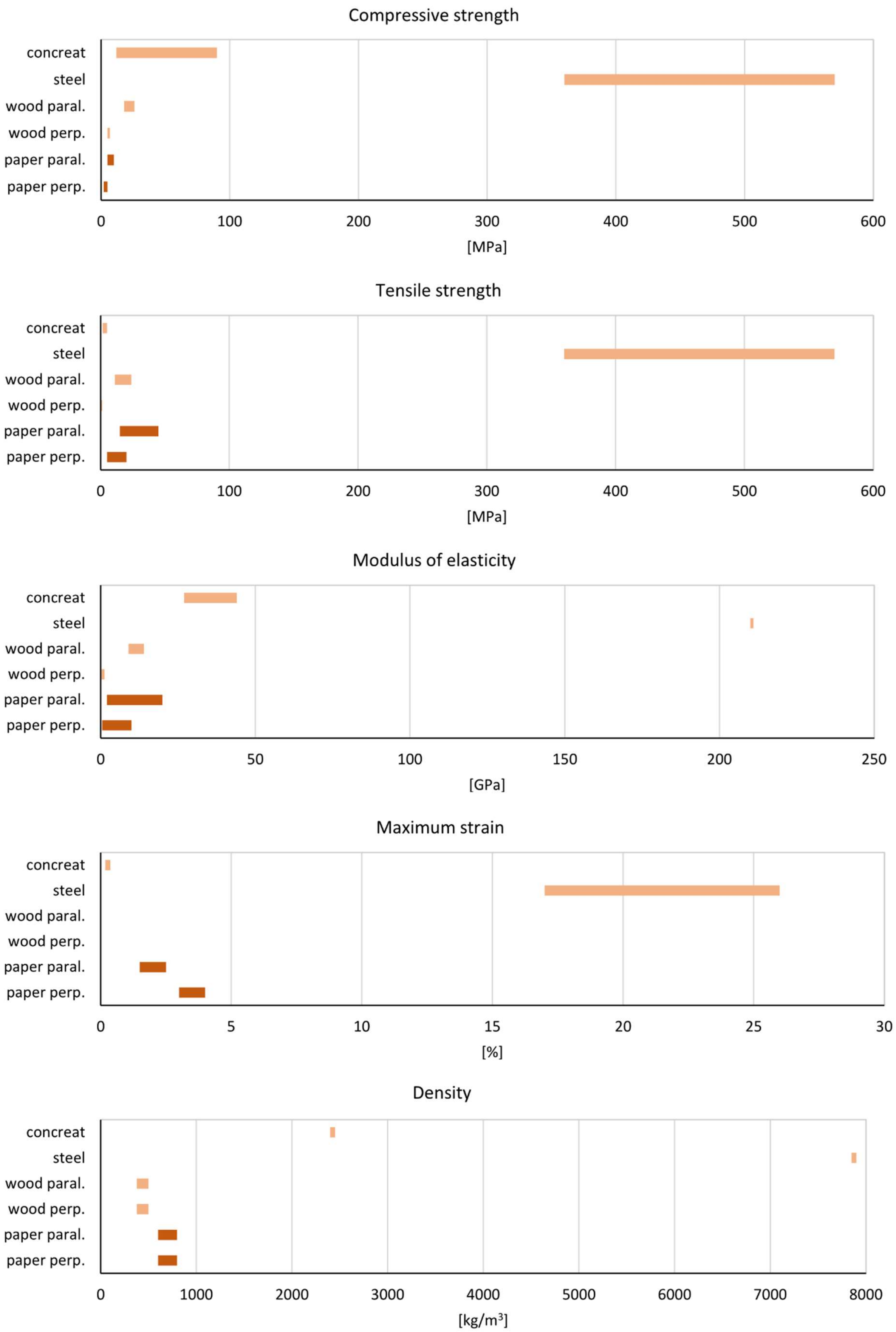

Figure 2.10. Mechanical parameters of commonly used building materials and paper, paperboard.

Table 2.2. Mechanical parameters of commonly used building materials and paper, paperboard.

Material/ Parameter	**Compressive strength [MPa]**	**Tensile strength [MPa]**	**Modulus of elasticity E [GPa]**	**Maximum strain [%]**	**Density [kg/m³]**
Concrete (PN-EN 1992-1-1, PN-EN 1991-1-1)	12-90	1.6-5	27-44	0.18-0.28	2400
Steel (PN-EN 1993-1-1)	360-570	360-570	210	17-26	7850
Wood parallel to the grain (PN-EN 338)	18-26	11-24	9-14	-	380-500
Wood perpendicular to the grain (PN-EN 338)	5-6	0.3-0.4	0.3-0.5	-	
Paper and paperboard machine direction (MD) [58]	5-10	15-45	2-20	1.5-2.5	600-800
Paper and paperboard cross-machine direction (CD) [58]	2-5	5-20	0.5-10	3-4	

2.1.3. Thermal properties of paper-based products [11]

When using paper products in architecture, an important issue is to meet the requirements of adequate thermal insulation of a building envelope. The basic thermal properties of building materials are thermal conductivity (λ) and specific heat (cp). Knowing the thermal conductivity coefficient allows for the calculation of the U-value parameter of the building envelope, which directly affects the energy consumption of the building. The specific heat and density of a material determine the dynamics of heat flow through this material, which affects the thermal stability of the building envelope.

International standards are the primary source of data on material parameters. Thermal parameters can be found in two standards: ISO 10456:2007 and ISO 6946:1999 (standard withdrawn and replaced by a newer one, but the current standard does not have a table with thermal values of materials) [68,69]. In Table 2.3, the thermal parameters for several typical building materials are listed and compared with paper products, which can be found in the above standards. The materials are ranked from the highest to the lowest thermal conductivity coefficient.

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[11] Research from this section was conducted by Paweł Noszczyk.

Table 2.3. Thermal parameters values of paper-based products and selected typical building materials, according to the international standards EN ISO 10456: 2009 and EN ISO 6946: 1999.

Material	**Thermal Conductivity**	**Specific heat**	**Density**
	λ [W·m^{-1}·K^{-1}]	cp [J·kg^{-1}·K^{-1}]	ρ [kg·m^{-3}]
Stainless steel [1]	17.00	500	7900
Reinforced concrete (2% steel) [1]	2.50	1000	2400
Solid brick [2]	0.77	880	1800
Water [2]	0.60	4190	1000
Paper[2]	**0.25**	**1460**	**1000**
Cardboard [2]	0.14	1460	900
Aerated concrete [2]	0.14	840	400
Wood [1]	0.12	1600	450
Cellulose granulate [1, 2]	0.039	1600	32
EPS (expanded polystyrene) [1, 2]	0.032	1450	15
Mineral wool [1, 2]	0.030	1030	100
Air [1]	0.025	1008	1.23
Aerogel [3]	0.013	no data	150
Vacuum Insulated Panels (VIP) [3]	0.007	no data	180

[1] Data based on the EN ISO 10456: 2009 standard
[2] Data based on the standard EN ISO 6946: 1999
[3] Manufacturer's data included in the product technical sheet

When analysing the thermal parameters for paper-based materials, air must also be considered. Air is a good thermal insulator and occurs in the form of closed, nonventilated air voids in the structure of materials such as corrugated cardboard, honeycomb panels, and paper tubes. No thermal conductivity coefficient is given for closed air voids. Thermal insulation is determined by the thermal resistance (R) of an air layer of a specific thickness. These values can be found in the ISO 6946:2017 and ISO 10077-1:2017 standards, and they are listed below in Table 2.4 [70,71].

Another source of thermal material parameters can be databases of computer programs used for thermal calculations in civil engineering. A popular program for hygrothermal calculations is the WUFI software. The databases of this program contain only information about paperboard (solid and homogeneous material). The thermal conductivity is given as 0.42 W/mK (for a density of 120 kg/m^3 and a heat capacity of 1500 J/kgK). The Fraunhofer Institute-IBP is quoted as the source of the data. Information on the thermal properties of paper-based products can also be found in the Integrated Environmental Solutions (IES) database: the thermal conductivity of paperboard laminate is specified as 0.072 W/mK (for a density of 480 kg/m^3 and a heat capacity of 1400 J/kgK), and the thermal conductivity of cellulose fill is 0.039 W/mK (for a density of 48 kg/m^3 and a heat capacity of 1381 J/kgK).

Table 2.4. Thermal resistance values, unventilated air voids, closed surfaces with high emissivity according to the international standards EN ISO 6946:2017-10 and EN ISO 10077-1:2017.

Thickness of air layer	**Thermal resistance - Upwards****	**Thermal resistance - Horizontal****	**Thermal resistance - Downwards****	**Thermal resistance - Horizontal****
[mm]	R [$m^2 \cdot K \cdot W^{-1}$]	R [$m^2 \cdot K \cdot W^{-1}$]	R [$m^2 \cdot K \cdot W^{-1}$]	R [$m^2 \cdot K \cdot W^{-1}$]
0	0.00	0.00	0.00	-
6	-	-	-	0.127
5	0.11	0.11	0.11	-
7	0.13	0.13	0.13	-
9	-	-	-	0.154
10	0.15	0.15	0.15	-
12	-	-	-	0.173
15	0.16	0.17	0.17	0.186
25	0.16	0.18	0.19	-
50	0.16	0.18	0.21	0.179
100	0.16	0.18	0.22	-
300	0.16	0.18	0.23	-

* Columns 1-4 based on EN ISO 6946:2017-10; column 5 based on EN ISO 10077-1:2017
** Direction of heat flow

Thermal conductivity of paper

The first mention of the thermal conductivity of a sheet of paper can be found in [72]. It gives the thermal conductivity coefficient for oil impregnated paper (λ=0.184 W/mK) and for rice paper (λ=0.046 W/mK) based on data from 1923. Thermal conductivity for uncoated sheet paper can often be found in works on printing: 0.13 W/mK [73], 0.11-1.12 W/mK, various types of copy paper (coated paper) 0.08-0.18 W/mK [74]. In literature [75] the specific heat parameter for several types of copy paper can also be found (see Table 2.5).

Table 2.5. Thermal parameters of commercially available copy paper according to the literature [75].

Description	Density	Specific heat	Thermal conductivity	Thermal diffusivity
	ρ [kg·m^{-3}]	cp [J·kg^{-1}·K^{-1}]	λ [W·m^{-1}·K^{-1}]	$\alpha \cdot 10^6$ [m^2·s^{-1}]
Low-density copy	625	1650	0.0808	0.0783
Uncoated free sheet	773	1550	0.1094	0.0913
Offset, uncoated	839	1150	0.0858	0.0889
Glossy, coated	1190	1250	0.1756	0.1180

The low thermal conductivity coefficient for paperboard was measured and described by Wang et al. [76]. At a temperature of 20°C and a density of 305.8 kg/m^3, the thermal conductivity of the paperboard was 0.065 W/mK.

Thermal conductivity of paper-based products

Thermal analyses of corrugated cardboard were conducted by Asdrubali et al. [77]. Recycled packaging material was used for the study. The thermal conductivity was determined using a guarded hot plate apparatus (own construction based on steady-state heat flux methods). It was calculated for the C- and E-type corrugated cardboard for various combinations of the layer arrangement (Fig. 2.10). The same authors extended their research at work [78]. The experimental results of both studies are presented in Table 2.6. In addition, 2D and 3D numerical analyses were performed in the above work. The numerical analysis yielded thermal conductivity coefficients for corrugated cardboard in the range of 0.0460 - 0.0525 W/mK for C-flute; 0.0575 - 0.0710 W/mK for E-flute and 0.0490 - 0.0560 W/mK for sandwich configurations. The study showed slightly better thermal insulation parameters for the parallel-arranged wave compared to the perpendicular one. Unfortunately, the samples were not conditioned before testing (they were not dried to a constant weight). It should be remembered that the results of the thermal conductivity coefficient for materials tested under different boundary conditions (temperature and moisture of sample) should not be compared.

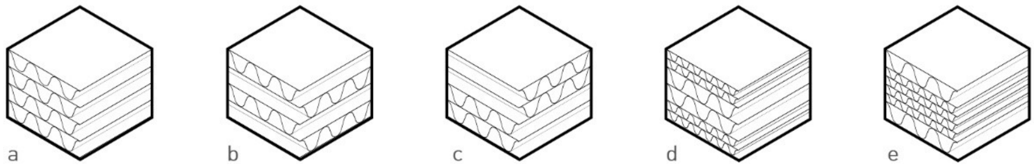


Figure 2.11. Samples used in the thermal analysis in [77,78]*; (a) parallel; (b-c) orthogonal; (d-e) sandwich.* [12]

Table 2.6. Thermal conductivity measured for various types of corrugated cardboard (at RH=30%), according to the literature[67,68].

Description	**Thickness of sample**	**Thermal conductivity**	**Bulk Density**
	s [mm]	λ [W·m^{-1}·K^{-1}]	ρ_{vol} [kg·m^{-3}]
8 parallel C-flute	33.0	0.0493	132.0
12 parallel C-flutes	50.0	0.0530	132.0
12 orthogonal (1x1) C-flute	50.0	0.0524	132.0
18 parallel C-flutes	75.0	0.0530	132.0
18 orthogonal (1x1) C-flutes	50.0	0.0524	132.0
16 parallel E-flute	39.0	0.0545	276.0
26 parallel E-flutes	51.0	0.0580	276.0
26 orthogonal (1x1) E-flute	51.0	0.0570	276.0
40 parallel E-flutes	76.0	0.0598	276.0
Sandwich with 4E-10C-4E	60.0	0.0547	153.0
Sandwich with 5C-8E-5C	60.0	0.0531	153.0

The thermal insulation properties of Honeycomb panels (see Figure 2.12) and 2 types of corrugated cardboard were tested by Cekon et al. [81]. The results (see Table 2.7) indicate that the honeycomb panels have approximately 40% worse thermal insulation parameters than corrugated cardboard. The thermal conductivity coefficient for the honeycomb panel increases with the height of the air voids (thickness of the panel).

The thermal testing of Honeycomb panels is also described by Salavatian et al. [82]. In this study, a model consisting of 2 complex elements, each 50 mm thick, was tested. For a honeycomb panel with a height of 50 mm and a density of 43 kg/m^3, the thermal conductivity coefficient value is 0.125 W/mK.

[12] Drawing by D. Jezierska.

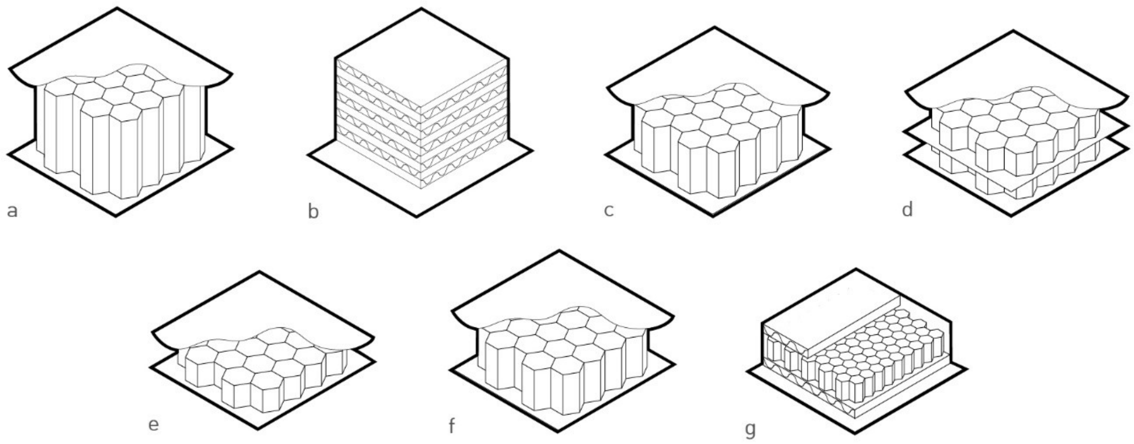


Figure 2.12. Samples used in the thermal analysis in [81]. [13]

Table 2.7. Thermal conductivity measured of honeycomb panel and corrugated cardboard for different heights of air voids, according to the literature [81].

No	Description	Thickness of sample	Thermal conductivity			Bulk Density
[-]	[-]	s [mm]	λ [W·m⁻¹·K⁻¹]			ρ_{vol} [kg·m⁻³]
			at 10°C	at 20°C	at 30°C	
a	HCP h=68 mm / w=16mm	69.662	0.1167	0.1341	0.1533	24.50
b	10 orthogonal C-flute	34.007	0.0486	0.0495	0.0539	89.52
c	HCP h=29 mm / w=14mm	30.400	0.0899	0.0957	0.1051	37.35
d	HCP h=2*17 mm / w=14mm	26.810	0.0727	0.0765	0.0826	47.93
e	HCP h=12,5 mm / w=13mm	13.268	0.0706	0.0745	0.0806	48.25
f	HCP h=17 mm / w=14mm	18.130	0.0773	0.0816	0.0882	38.72
g	2xB-flute+HCP h=14mm+2xB-flute	28.625	0.0624	0.0645	0.0678	129.02

HCP = honeycomb panel; h = high cells; w = wide cells high; w= cells wide

The thermal anisotropy of the paper was analysed by Gray-Stuart et al. [83]. A sheet of paper in the plane of its surface (machine and cross-machine direction) can show differences in the thermal conductivity coefficient of up to 33%. For selected types of paper, the values of thermal conductivity in the machine direction ranged from 0.45 W/mK to 0.72 W/mK, while in a cross-machine direction from 0.36 W/mK to 0.48 W/mK, the same sheets in the direction of their thickness had the lambda parameter much lower, i.e., in the range from 0.07 W/mK to 0.09 W/mK.

[13] Drawing by D. Jezierska.

In the above work, the thermal resistance (R) for the B-flute (0.061 or 0.064 m^2K/W) and C-flute (0.074 or 0.082 m^2K/W) corrugated cardboard was also determined. The differences in thermal resistance value arise because of different types of paper adopted in production.

2.1.4. Acoustic properties of paper-based products [14]

In architecture, the fundamental acoustic parameters of a component describe its sound absorption or insulation properties. The first of them is defined by the absorption coefficient α, which is one of the basic parameters used in room acoustics. Sound absorption affects speech intelligibility, acoustic comfort, and noise level (indirectly), along with several other factors. Furthermore, absorbent materials are widely used in noise mitigation, either as acoustic screens and barriers or as highly insulating wall fillings.

The sound insulation properties indicate the amount of acoustic energy not transmitted through the material (i.e. absorbed or reflected). A set of parameters can characterize the insulation features of a material. The laboratory-measured ones are:

- Transmission Loss (TL) in decibels [dB],
- Sound Reduction Index (R) in decibels [dB] (in ISO terminology).

Mentioned parameters could regard the different circumstances and therefore any comparisons should be made carefully with respect to the measurement method. The literature provides the results of the two parameters mentioned to describe the properties of paper sound insulation. They will be described and compared in this chapter.

The sound absorption coefficient is the ratio of the absorbed to incident sound energy. It varies from 0 to 1, where 0 corresponds to total reflection and 1 to total absorption. The absorption in the material occurs mainly through the conversion of sound energy into heat (i.e. by generating friction in the inner structure of a material). That is why porous or fibrous materials form the most common absorbers. The absorption coefficient in typical materials increases with frequency, and also to a certain point with the thickness of an absorptive layer [84].

The cellulose fibre is a frequently used absorber material, and consequently, its sound absorption properties were well researched over time. Arenas et al. [85] precisely predicted and measured unbleached cellulose under various humidity conditions. Trematerra and Lombardi [86]

[14] Research from this section was conducted by Aleksandra Klimek.

measured loose and bonded recycled cellulose. In both articles, cellulose reached the absorption efficiency of commonly used mineral fibre-based products. However, little information is available on the absorption coefficient of paper and paper-based products. The reason lies in the process of papermaking itself. Paper is formed by pressing and drying the cellulose, leading to a dense structure with clamped fibres. The friction cannot occur in the inner structure of the paper at a level as high as that initiated in the unprocessed cellulose. Therefore, the absorption coefficient was too low to constitute the paper as a good subject of study in the past.

Asdrubali et al. [78] explored the insulation properties of multiple layers of corrugated cardboard. The clear observation was the effect of the number of layers and sample surface density on TL increase. The more dense E-flutes corrugated cardboard had greater insulation properties than the C-flutes. Another conclusion was the effect of the orientation of the flutes. Parallelly oriented C-flutes samples had greater TL in lower frequencies and the orthogonal configurations outperformed in higher ones. This consequence of orientation could be beneficial in terms of use optimization.

In different work, Ricciardi et al. [87] demonstrated that an insulation panel could be easily constructed with multiple layers of waste paper. The measured sandwich panel was formed with two layers of textile fibres (2.5 mm each) with the waste paper layers filled. The Transmission Loss increased by about 5 dB in the whole frequency range, only by changing the waste paper thickness from 7 to 15 mm.

Paper has also proven to be an excellent insulation material in the work of Neri et al. [88] and Kang, Kim, and Jang [89]. In both works, the Transmission Loss of paperboard or corrugated cardboard reached high values. The more cardboard layers used, the greater the TL obtained. Effective insulation properties of paperboard are achievable due to the relatively high density compared to other sustainable materials.

The only published Sound Reduction Index results for the paper-based products were calculated analytically by Secchi et al. [90]. The work provides an analysis of ten structures and each of them was diversified into two to four different versions. Each sample was then rated with the grade: not convenient, medium, or convenient; according to its acoustic performance, transport and lightness, cost, and recyclability. The results are presented in Table 2.8 with a single value – Weighted Sound Reduction Index R_W.

Table 2.8. Weighted Sound Reduction Index and rating of exemplary paper-based panel structures [90] *compared to conventional lightweight constructions.*

Product/ Structure	**Description**	**Thickness [mm]**	**Weighted Sound Reduction Index R_W**	**Rating** [15]
Sandwich panel	Sandwich panel with perforated (Ø: 3 mm) honeycomb panel (PH), filling of cellulose fibre panel (C), and unperforated honeycomb panel (H). Honeycomb panels have 10 mm cells. Cellulose fibre density is 50 kg/m3	80: PH(15) C(50) H(15)	16 dB	Convenient
Sandwich panel	Sandwich panel with perforated (Ø: 3 mm) corrugated honeycomb panel (PH), filling of cellulose fibre panel (C), and unperforated honeycomb panel (H). Honeycomb panels have 8 or 5 mm cells. Cellulose fiber density is 60 kg/m3	60: PH(15) C(30) H(15)	16 dB	Convenient
Paper tubes wall	Partition of paper tubes (internal Ø: 300 mm), filled with cellulose fibre, with slits distributed on all tubes. Cellulose fibre density is 50 kg/m3	Paper tube internal wall: 10	24 dB	Medium
Paper tubes wall	Curved partition of paper tubes (internal Ø: 150 mm), filled with cellulose fibre, with slits distributed on all tubes. Cellulose fibre density is 80 kg/m3	Paper tube internal wall: 5	21 dB	Convenient
Conventional lightweight structures				
Plasterboard	Single plasterboard panel. R_W was calculated with Insul 9.0 software. Surface mass is 9.6 kg/m2	12.5	27 dB	-
Double beaverboard [91]	Double beaverboard panel (B), with the filling of Styrofoam (S) Surface mass is 6 kg/m2	36,4: B(3.2) S(30) B(3.2)	21 dB	-
	Double beaverboard panel (B), with the filling of mineral wool (M), constructed with timber studs Surface mass is 20 kg/m2	60: B(5) M(50) B(5)	35 dB	-

2.1.5. Protection against water and humidity [16]

To be used in the construction industry paper needs to be protected from various factors such as fire, mould, physical damages, water, and moisture. Water protection is especially important for

[15] Based on authors' rating from [90].

[16] Research from this section was co-authored with Szymon Misiurka and Sonia Zielińska.

paper durability, as paper mechanical strength decreases by approximately 10% with every 1% increase in material moisture level [24]. Impregnation, lamination and coating can significantly reduce paper's vulnerability to water, some methods can also provide fire protection or surface strengthening [92].

Hydrophobic paper impregnation is applied in various sectors of industry, to improve products properties. A significant amount of research into bio-based and biodegradable impregnation methods has been conducted, especially in the field of food packaging. The growing demand for environmentally friendly packaging has resulted in numerous studies on innovative paper impregnation methods. Biopolymers, such as polysaccharide derivatives (e.g. starch acetate), lipids (e.g. waxes and fatty acids) or polylactic acid have been proven to increase the water resistance and water vapour barrier of paper. High hydrophobicity was also achieved by using composite coatings, combining lipids with proteins or polysaccharides [92–94]. Traditionally, rosin-alum sizing agent and synthetic sizes such as alkyl ketene dimers or alkenyl succinic anhydrides have also been used to increase the hydrophobicity of paper materials [95–98]. Superhydrophobic and oleophobic paper surfaces have also been successfully prepared by using atmospheric pressure plasma etching. A novel dielectric barrier discharge operating in a helium-oxygen mixture has been used to etch organic material from the paper surface and create hierarchical topography. After that, the thin fluorocarbon film is deposited to modify the surface energy [99]. The selected research from this area and their key finding are presented in Table 2.9.

The simplest way to obtain water-resistant paper is to coat it with commercially available water-repellent materials with low surface energy like fluorinated polymers, polysiloxanes, or higher alkanes. However, fluorinated compounds should be avoided as a result of their negative environmental impact and toxicity.

Paper laminated with synthetic polymers, such as low-density polyethene or polypropylene, is difficult to recycle. After disposal, it is usually landfilled and becomes a source of microplastic [100]. Bio-based plastic layers are used as an alternative to LDPE (low density polyethylene). The most important biobased synthetic polymer is poly(lactic acid) (PLA). The main disadvantage of such a solution is the difference in the biodegradation environment for cellulose and PLA, which biodegrades only under industrial compost conditions.

One of the classical methods of paper hydrophilization is the use of wax [101]. Wax-coated paper has some disadvantages, low thermal resistance and poor crack resistance. Environmentally friendly and water-resistant paper-based materials are still being developed. One of such approaches is to use hydrogenated vegetable oils incorporated into an aqueous dispersion of hybrid maleimide styrene nanoparticles [102].

Table 2.9. Selected research regarding paper impregnation for the packaging industry. (WA – water absorption, WVP – water vapour permeability)[92].

Reference	Impregnated material	Impregnation technique	Key conclusions
[103]	Micro corrugated cardboard	2% polylactic acid (PLA) solution in chloroform – alone and its combinations; applied by a metal bar coater	PLA coating reduced the WA 18.4 times and WVP nearly 10 times in comparison to the uncoated samples
[104]	Kraft paper (75 g/m^2)	Cassava starch acetate solution in chloroform; applied by samples immersion	The coating reduced WVP about 4 times in comparison to the uncoated samples
[105]	Kraft paper	Chitosan emulsion and chitosan with palmitic acid emulsion (C+PA); applied by a wire bar coater	The coating (C+PA) reduced WVP by 51% and WA by 41% in comparison to the uncoated samples
[106]	Paperboard (180 g/m^2)	1-5% polylactic acid (PLA) solution in chloroform; applied by a wire bar coater	The 5% PLA coating reduced WVP 25.5 times and WA 17.9 times in comparison to the uncoated samples
[107]	Two-layer paperboard (300 g/m^2)	Hydrophobic starch matrix with stearic acid; applied by a film coater	The coating reduced WA about 10 times in comparison to the uncoated samples
[108]	Single-side coated paperboard (300 g/m^2)	0.5-4% polylactic acid (PLA) solution in chloroform; applied by electrospraying	The 1% PLA solution was indicated as the most effective.
[109]	Paperboard (213 µm thick)	Whey protein concentrate-beeswax-sucrose suspension in different ratios; applied by brush	The coating reduced WVP more than 2 times and WA more than 8 times in comparison to the uncoated samples. The beeswax content was crucial for the water resistance of the samples.
[110]	Coated paper	Carnauba wax-mica-sodium caseinate-glycerol dispersion; applied by a control coater	The WVP decreased with the amount of carnauba wax and mica, increased with the amount of glycerol and sodium caseinate
[111]	Cardboard (250 g/m2)	Chitosan suspension with different levels of acetylation (2% and 48%)	The C-48 coating provides higher hydrophilicity than C-2 coating

Paper lamination and impregnation is an extensive field of research, however, they are usually undertaken for the packaging, food or printing industry. The results could, to some extends, serve as a guide in choosing the optimal methods for waterproofing paper-based building elements, but there is still a significant lack of knowledge in this area. Architecture and structural use of paper require a different combination of characteristics than in traditional applications. Factors such as incombustibility, resistance to mechanical damages, extreme weather conditions and ultraviolet radiation, stiffness or aesthetic values should be taken into account.

Although several successful paper-based structures and buildings have already been constructed, they were usually focused more on structural stability than impregnation techniques. The most commonly used waterproofing methods can be categorised into three main approaches and their combinations:

- layering paper-based core with traditional, waterproof materials, like metal sheets, wood cladding or mineral boards;
- covering paper with paints and wood varnishes, usually acrylic or polyurethane-based;
- laminating with polymer films, usually polyethylene or polyvinyl chloride.

2.1.6. Protection against fire [17]

One of the most crucial difficulties to overcome when designing with paper is fire safety – as with most bio-based building materials, paper is easily flammable. However, the combustibility of the material depends on the type of paper-based products used. While products composed of thin sheets of paper with air cavities in between, such as corrugated cardboard and honeycomb panels, ignite and spread fire quickly, thick layers of paperboard present certain fire protection properties. The outer layers of thick paperboard chars, forming a protective layer on the rest of the material – a similar mechanism can be observed in wood [39].

Despite this mechanism, additional fire retardant protection of paper-based building elements is necessary to ensure users safety. Although the legal regulation varies between countries, in most cases it is required that building elements are non-combustible or fire-resistant.

There are three main approaches to reducing the flammability of cellulosic, including paper-based elements.

[17] This section was a part of s an article published in Architecture, Civil Engineering, Environment [206].

- Material additives during production, e.g. phosphorus compounds, that provide effective long-term protection. However, the presence of retardants, e.g. inorganic salts, in the material may interfere with elements bonding and have an abrasive effect on cutting tools [112].
- Fire retardants applied to the end product, including immersion in water-based solutions and coatings, provide a uniform, seal coating on the surface of the final product. This technique usually requires less impregnating agent and facilitates recycling due to limited penetration into the material, but is more sensitive for air humidity changes and may increase the roughness of impregnated surfaces [113,114]. Some coatings can also provide water protection.
- Layering with other, fire-resistant materials, e.g. metal sheets or mineral boards facilitate the recycling process due to the possibility of separating materials. Moreover, it can provide additional protection against water and mechanical damage. However, finishing layers imply increased weight and the need for additional joins between materials.

The role of fire retardants (FR) is to increase the fire safety of the impregnated material by reducing its contribution to a possible fire. This effect can be achieved by delaying the moment of ignition of the material and reducing the combustion intensity and the spread of the fire. Several mechanisms of disruption of the combustion process at different stages can be distinguished.

- Formation of coatings that slow down the transport of heat to the protected material, delaying the moment of ignition;
- formation of a char layer on the surface of the material in the initial stages of combustion, which slows down heat transfer;
- emission of non-combustible gases at high-temperature conditions (e.g. water vapour);
- endothermic degradation of FR compounds, that reduces the temperature of the material.

Besides ensuring fire safety, FR should be harmless for people and the natural environment during normal use of the treated objects, as well as during combustion [115].

A large variety of chemical compounds can be applied as fire retardants, especially inorganic salts of phosphorus, boron, chlorine or sulphur. Furthermore, organic substances, like urea and melamine can also be used [115]. In most commercial FR several compounds are combined to employ various retardancy mechanisms and achieve more effective protection. In the last years, the use of some FR has been either discouraged or prohibited due to their toxicity and harmful effects on people health and the environment. The widely used halogenated FR (especially brominated FR) have been proven to emit toxic halogenated compounds during ignition, that accumulates e.g. in crop plants, penetrate the human body and cause carcinogenic effects [116]. Therefore, it is crucial to use FR that are not only effective but also safe. Besides experimental studies on the use of organic compounds like tannic acid [117], guanidines [118,119] or plant extracts as FR, e.g. green coconut shell or banana pseudostem [120,121], widely used groups of non-toxic FR are borates and phosphates.

Borates are one of the most efficient and well-studied FR for wood and other cellulosic materials, such as bamboo [116,122] or paper [123]. They are also incorporated as a FR additive in the production of paper-based composite materials or laminates [124–126] and into commercial cellulose-fibre thermal insulation [3]. Borates can also act on these materials as a protection against insects, bacteria and fungi [127]. The two most widely-used FR compounds are boric acid and borax (sodium borate), both non-toxic and cheap. Both of them act by physical mechanism, forming a glassy protective coating on the impregnated surface, as well as chemical, by promoting a char formation and releasing water vapour at high temperature [116,128,129]. However, as described by Yu et al., borax presents better performance in slowing down the heat release while boric acid results in a lower amount of total heat released. Therefore, to achieve the best, synergic results the study suggested the use of both compounds in a ratio of 1:1 [122], which also enables solutions of higher concentration to be produced. The differences between the compounds are also noticeable in the degree of resistance to humidity. While boric acid is resistant to water vapour, changes in humidity may cause efflorescence on surfaces coated with borax [112]. Moreover, none of the borates has the ability to chemically bond with cellulose, which may have a negative effect on the durability of the protection, however, allows easy separation of the impregnating agent during the recycling process.

A wide range of Phosphorus-containing compounds can be used as a FR, including organic compounds (e.g. Trialkyl Phosphate or Phosphoramide) and inorganic ones [130,131]. The most popular are inorganic salts of Ammonium Phosphate and Diammonium Phosphate. Like boron compounds, phosphates are non-toxic and soluble in water however, they are more sensitive to changes in air humidity [112]. The main fire retardancy mechanism of phosphates in the condensed phase involves the formation of a non-combustible char layer on the impregnated surface [116]. Moreover, the retardants can also inhibit flame in the gas phase [132]. Like borates, inorganic phosphorus salts do not chemically bind to cellulose.

Most of the abovementioned FR are water-soluble, hygroscopic and sensitive to air humidity. Paper elements are also particularly sensitive to moisture, therefore it is especially important to protect impregnated paper from contact with water. This can be achieved by cladding the element with other materials, such as membranes and metal sheets or providing an additional layer of waterproof impregnation.

2.1.7. Connections and lamination of paper-based components [18]

As paper is prone to damage under local stresses, the use of mechanical joints (e.g. screws) is limited and adhesives provide more stable connections between paper-based elements [133]. Mechanical joints are used mostly between paper and other, stiffer materials or in connections of linear elements, such as paper tubes. They usually require incorporation of some harder materials (e.g. wood-based tenon inside a paper tube) into connected component, as screws and bolts must not be screwed directly into the paper.

Bonding is the most widely-used technique of joining paper elements, also in architecture-related applications. On the other hand, glues have an important contribution to the sandwich elements' environmental impact and recycling ability, as well as cost or ease of production. The ideal adhesive for paper-based building components should facilitate application over large areas (which implies longer open time), offer a good initial tack and short setting time. Moreover, the product should be environmentally friendly, inexpensive and easily available on a market, to match the main advantages of paper.

Adhesives for paper

Adhesive is a substance that is capable of bonding two or more surfaces together firmly and permanently. The term adhesive covers a wide range of materials, differing from each other by chemical structure, physical properties, and the mechanism of hardening. The adhesive compositions are generally complex; except for base polymer material, they also contain fillers, pigments, stabilizers, plasticizers. The adhesive composition takes into account the desired final joint properties, application method, and acceptable cost. Adhesives are most often liquid at first and harden after some time after application [134,135].

The most common surface forces at the adhesive-adherent interface are van der Waals forces, but acid-base interactions and hydrogen bonds may also contribute to adhesion forces. Due to the porous nature of paper, mechanical adhesion is an important phenomenon. Paper is highly porous in structure, and thus it absorbs liquid easily through capillary forces. Chemical adhesion also

[18] Research from this section was co-authored with Szymon Misiurka and Sonia Zielińska.

plays a role in common adhesives. The most popular adhesives, such as starch or PVA (polyvinyl acetate and polyvinyl alcohol), are polar [19], just like paper. This results in good material compatibility. Polyolefins, metals, and glass are nonpolar adherents. For paper adherends, the mechanism of adhesion is usually complex and takes into account various kinds of interactions [136]. Cellulose fibres contain many hydroxyl groups and that makes paper hydrophilic [137].

Adhesives can be simply divided into natural and artificial ones. Natural adhesives come from raw materials from plants and animals. They are most often environmentally friendly; however, they usually offer moderate bonding strength and water resistance. The most popular natural adhesives used for paper gluing are as follows.

Starch

In the timber industry, starch is used due to the availability of its raw materials, low cost, simple process, good adhesion, and low environmental impact. Despite the advantages, starch shows poor water resistance, high permeability, and limited mechanical properties [138,139]. To obtain better properties, starch is often modified. This operation allows stronger bonds to be enhanced, improved water resistance, better processing, and most importantly, better affinity for cellulose. One of the possible modifications is dextrinization [20]. Borated dextrins are especially popular in paper lamination, corrugation, or tube winding. Isocyanates are another group of chemical compounds that are often used as starch modifiers, due to the improvement of properties such as bond strength and water resistance [138,140].

Cellulose

Cellulose is a natural linear polymer and its properties depend on the raw materials from which cellulose comes from. Cellulose occurs in semicrystalline structures and forms a lot of hydrogen bonds, which is why cellulose is insoluble in traditional solvents. Consequently, pure cellulose is not used as an adhesive [141]. To use cellulosic material in adhesive joints, cellulose derivatives must be obtained. For example, cellulose ethers improve the adhesion and water retention of adhesion mortars. The properties of cellulose ethers depend on the content of the etheric groups and the degree of etherification, which is related to molecular weight [142]. Nitrocellulose is the

[19] The molecules of polar substances have regions of positive and negative charge, resulting in stronger bonds between them.

[20] Dextrinization is a type of hydrolysis process that occurs when dry starch with added acidic substances is subjected to high temperature. As a result, starch is broken down to sugar called dextrin

other cellulose derivative that has better adhesion and better solubility (cellulosic nitrates are soluble in esters, ketones, glycol ethers, and ether-alcohol mixtures). Nitric derivative is used mainly in paints and impregnates [141,143].

Artificial adhesives are polymeric materials made by chemical reactions. They usually offer high bonding strength and water resistance while having toxicity and environmental impact higher than those of natural ones. The most popular artificial adhesives used for paper gluing are as follows.

Copolymer Ethylene – Vinyl Acetate (EVA)

A large proportion of artificial adhesive materials are hot-melt adhesives. They are used mainly in the footwear, packaging, bookbinding, and wood industries. Hot melts are solid thermoplastic compounds that are melted while applied on surfaces. They do not require any solvent, so they do not show any side compound emission. Among hot melt adhesives, the most popular is the ethylene-vinyl acetate copolymer, EVA [144]. Properties of EVA adhesives depend on the content of vinyl acetate (VA) in polymer chains, which ranges from 18-40%. The less VA is present in the chain, the better adhesion to nonpolar materials, and the higher mechanical strength are achieved. The addition of VA leads to better adhesion to polar surfaces (for example, paper), higher tack, and greater flexibility [145].

Polyvinyl acetate (PVA)

PVA is the most common adhesive material, used primarily as an ingredient in school glue. It is a thermoplastic material produced in the polymerization reaction of vinyl acetate, which is often used in wood composites because of its good properties. Production of polyvinylidene (PVA) is cheap, the material is soluble in water, and the material has a low impact on the environment, because of its zero toxicity. Moreover, it has high initial tack, good biodegradation resistance, forms hard films, which have good weather resistance, and does not dissolve in water, petroleum fuels, and oil. Unfortunately, the mechanical properties of PVA are relatively weak and show limited bond strength and poor resistance to creep under load [146,147]. PVA adhesives are widely used in paper and timber-based products industry.

Phenolic-formaldehyde resin, PF

These resins were the first conventional, artificial polymers received in history. PF joints have high bonding strength, good water resistance, good chemical stability, and good heat and wear resistance. They are used in plywood manufacturing as both adhesives and industrial impregnates. The most serious drawback of PF is formaldehyde release. As a toxic compound, formaldehyde has a great impact on the environment and can be very harmful to living organisms. Another drawback is the long curing time, which requires longer hot-pressing while producing composites, and a higher hot-pressing temperature. These features have an impact on the economics of composites manufacturing. Accelerating curing can be reached with the addition of various resins with a shorter curing time or the addition of catalysts (for example, esters, urea, amides) [148–150].

Urea-formaldehyde resin, UF

Urea-formaldehyde resins are produced in the process of various reactions of urea and formaldehyde monomers. UF resin is a thermosetting material. Additionally, some modifiers may decrease the water resistance of UF resin. The advantages of using this adhesive material are its low cost of production, short curing time, high performance, and lack of colour [151,152].

Epoxy resin

Epoxy resins are a group of highly reactive compounds, which means that it can react with various curing agents. These resins show high adhesion to different surfaces (used for polymers, ceramics, and metals), curing without the release of side compounds, high chemical stability, good mechanical, cohesive, and adhesive strength of joints. The final properties may be designed by creating composites with special fillers, for example, silica nanoparticles can improve strength, durability, workability, and flexibility. Epoxy adhesives are efficient and require less material to join two surfaces than other adhesives [153,154]. In addition to adhesives, epoxy resins may also be used as impregnates because of their chemical and water resistivity.

One of the most important aspects to be considered when selecting an adhesive for paper-based building elements is the environmental impact. Ecological properties are the primary reason for implementing paper as a building material, however, adhesive choices may significantly reduce this important quality. The lowest environmental burden can be associated with fully natural adhesives, like starch, natural rubber, cellulose, gelatin or chitin. However, the limited strength, water and thermal resistance can restrict their application. Another approach toward less environmentally damaging adhesives is the production of artificial, however bio-derived materials, that may replace ones obtained from fossil fuels. Examples of such substances can be tannin-base resins [155,156]. Currently, the balance between ecology and availability, price and ease of application is usually obtained by the use of PVA adhesives.

Furthermore, not only the type, but also the amount of adhesive used imply the environmental impact of the composite. Therefore, it is crucial to determine the minimum thickness of the adhesive layer required to provide a uniform bond between surfaces.

Moreover, the impact of the adhesive on paper recycling process should be taken into consideration. During the recycling process, paper waste is mixed with water and heated to 80-120° C. In such conditions, some adhesives may form a sticky slime that adheres to the paper machine. This problem is usually solved in two ways – by using non-redispersible glues, such as hot melts, that can be removed by sorting machines after grinding into small pieces, or by opting for water-soluble adhesives, that may be washed out of pulp suspension [157,158].

2.1.8. Environmental impact of paper-based components

Paper is one of the most ecological man-made materials: biobased, renewable, suitable for recycling and biodegradation. On the other hand, paper and pulp production is one of the largest sectors of the global industry, resulting in a significant overall environmental impact. Moreover, merely using paper as a building material does not guarantee a reduction in the environmental impact of a structure. In this section, various factors that affect the environmental properties of paper and paper-based building elements are discussed.

Paper production

Modern paper production is a complex, high-precision technological process that converts a fibrous raw material into pulp and pulp into paper (see Figure 2.13). Although the process may vary depending on the raw material, end product, and technology, the four steps can be distinguished [159,160].

- Raw material preparation – selection, cleaning and chopping wood or other cellulosic materials used in production. This step is necessary only when paper is produced from virgin fibre.
- Pulping – a process of cellulose fibres separation and lignin removal from the raw material. There are three types of pulping process: chemical, mechanical and recovery (from recycled fibres). Mechanical pulp is produced by grinding wood chips. This technique has high energy demand but is highly effective – the yield of the process is over 90%. However, fibres in mechanical pulp are stiffer, and the suspension has high lignin content. In the chemical pulping process wood chips are cooked with chemical compounds, that separate lignin from the fibres. Nowadays, the most common pulping method in kraft cooking – with sodium hydroxide and sodium sulphide. Chemical pulping has high energy dement, but low carbon dioxide emission [161]. The process is less effective than mechanical pulping, however, it results in more flexible fibres with lower lignin and hemicellulose content, suitable for the production of higher quality, stronger paper. The residues from chemical

pulp cooking, containing cooking chemicals and dissolved organic material, are called black liquor [159]. In the case of recycled fibres, there is no need for lignin removal. Instead, waste paper is repulped and the pulp suspension is cleaned and deinked to produce pulp suitable for papermaking. Pulping process is the most energy-consuming part of the production, however, recycled-fibre pulp requires significantly lower energy input than standard pulping [161].

- Pulp modification – washing, cleaning and bleaching. Pulp can be modified, depending on the desired end product properties, with additives such as fillers (e.g. clay, talc) or pigments. Bleaching increase the quality and brightness of printing paper and prevents yellowing over time, but can be omitted in brown, e.g. packaging papers, reducing the use of water.
- Papermaking - the prepared pulp is fed into the paper machine, where the water is removed and fibres are pressed to form paper sheets [133].

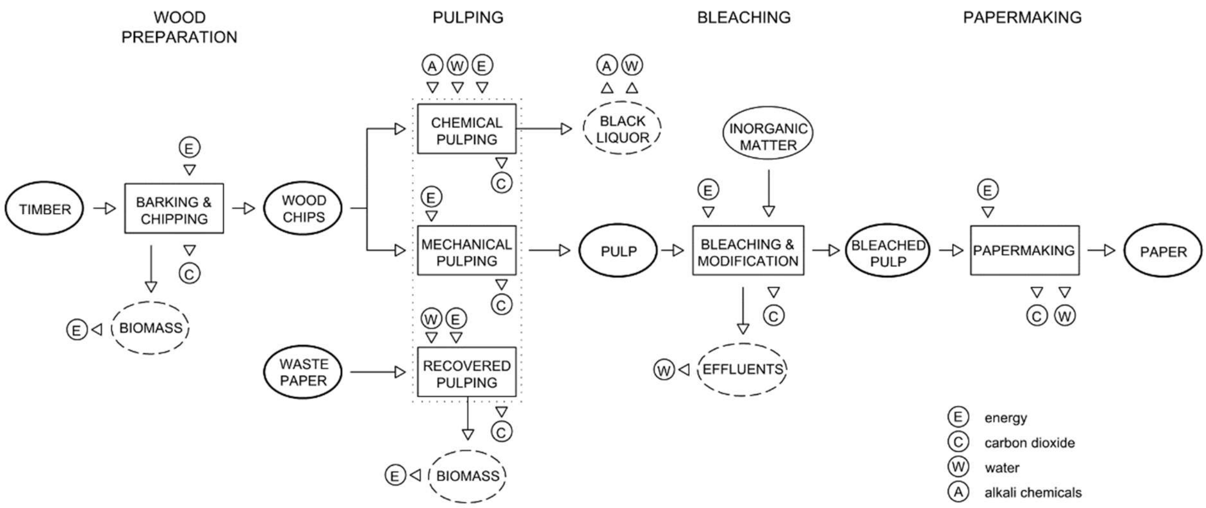


Figure 2.13. A simplified material flow in paper production process.

The environmental impact of paper production varies significantly depending on the technology, type of paper produced, and source of energy. However, there are four main impact areas.

- Energy consumption. According to Sun's analysis, production of one metric ton of paper requires an average of 28.26 GJ of energy, ranging from approximately 12 GJ in Nordic countries to 37 GJ in Brazil [162]. In 2018, the paper industry in Europe consumed 1 312 508 TJ of energy, with an average of 14.20 GJ per 1 ton of paper. Most of the energy consumed was obtained from biomass, a large amount of which is process residues [163]. Pulping is the most energy-consuming part of production.

- Carbon dioxide emission. On average, the production of 1 ton of paper results in about 950 kg of carbon dioxide equivalent emissions. However, the emission depends mainly on the type of fuel used in energy production. Therefore, in Nordic countries, where renewable energy is used, the emission is approximately 250 kg, while in China, with coal-based electricity, it is approximately 1700 kg [162]. In 2018, the European paper industry was responsible for the emission of 42 Mt of CO2, with an average of 400 kg per 1 t of paper [163].
- Water consumption. Water plays an essential role in pulp and paper production. Production of 1 t of paper in modern paper mills requires on average 10-50 m^3 of water [164]. Some of the water can be used in closed loop; however, a significant reduction of water consumption is not possible without compromising the quality of the paper. The highest amount of fresh water is used in the chemical pulp making process (40%) and in paper machines (35%) [165]. In 2018, the European paper industry consumed 3 481 million m^3 of water, 90% of which was later returned to the source [163].
- Wastewater treatment. The global pulp and paper industry produces approximately 3 billion m^3 of wastewater every year, which represents 42% of the global production of industrial wastewater [164]. The most polluted effluents, containing more than 300 different compounds, are produced in the bleaching process. The wastewater after chemical recovery is usually used in the closed loop for several production cycles, then cleaned and released back to the environment. The residues from wastewater processing are incinerated and the obtained energy is used in the production process [160].

Due to ecological reasons, law regulation, and the increasing cost of energy and water, the pulp and paper industry is constantly developing to reduce its environmental impact. The most significant changes are related to the use of renewable energy, reduction of water consumption, and toxic emissions. In Europe, between 1991 and 2018, the energy consumption per unit of produced paper was reduced by 20.6%, the water consumption by approximately 45% and the total emission of CO_2 by 45.2% [163].

Paper recycling

Paper and paper-based products can be recycled, biodegraded or incinerated for energy recovery. According to the analyses, recycling is the most sustainable way of dealing with paper waste [161,166]. The paper recycling rate for European Union was 72% in 2019. The highest recycling rate was obtained in newsprint (93%) and packaging paper (75%), while speciality and household papers are usually not recycled [163]. The aim of paper recycling is to reuse cellulose fibres, while removing the non-fibrous component of the paper. With each recycling process fibres are shortened, compromising the quality and strength of the produced paper. Therefore, recycled fibres are usually mixed with virgin ones during new paper production.

Apart from recycling, incineration and biodegradation can be used for the recovery of paper waste. These methods are implemented especially for short-fibre papers (e.g. tissues) and speciality papers with coating and additives that hinder the recycling process. The biodegradability of paper depends on its composition, in particular the lignin content, which delays the process. Therefore, bleached and chemical pulp paper (with lower lignin content) can degrade faster in the composting environment than mechanical pulp paper [167].

Factors influencing the ecological impact of paper-based products

Although paper itself can be considered a highly ecological material, the overall environmental impact of paper-based building materials is highly influenced by further stages of production, such as gluing, laminating, or impregnating.

The two factors that play the most important role in paper environmental assessment are fossil fuel consumption and biomass/land use. Land use decreases with the use of recycled fibre, while fossil fuels increase slightly. However, recycled fibres significantly reduce the total environmental impact of paper [80]. The most effective way of reducing fossil fuel consumption is to use renewable energy sources. The less processed the paper product is, the lower its environmental impact; speciality paper, highly bleached, with chemical additives or surface treatments can increase water and energy consumption several times compared to, e.g., brown packaging paper [165].

When considering paper-based products as thermal insulation, materials can be selected on the basis of their thermal resistance per amount of material used. Corrugated cardboard and honeycomb panels can be produced from the same type of paper, although their weight and thermal conductivity vary depending on the geometry of the product. For the purpose of the analysis, the reference thickness of popular paper products required to provide a thermal resistance of 1 m^2K/W was calculated. The weights of the referenced thickness samples are presented in Figure 2.14 and Table 2.10. It can be concluded that 2-layer, A-flute corrugated cardboard and 25 or 12.5 mm thick honeycomb panels offer the most efficient material use.

Table 2.10. Selected properties of paper-based insulative materials [168].

material	type	weight [kg/m²]	weight [kg/m³]	thermal conductivity [W/mK]	reference thickness [mm]	reference weight [kg/m²]
paper honeycomb panel	50 mm thick	1.80	36	0.125	125	4.50
	25 mm thick	1.00	40	0.095	95	3.80
	12,5 mm thick	0.60	48	0.075	75	3.60
corrugated cardboard	A-flute, 2-layer	0.40	80	0.047	47	3.76
	A-flute, 3-layer	0.55	110	0.047	47	5.17
	C-flute, 3-layer	0.50	125	0.053	53	6.63
	BC-flute, 7-layer	0.70	100	0.050	50	5.00

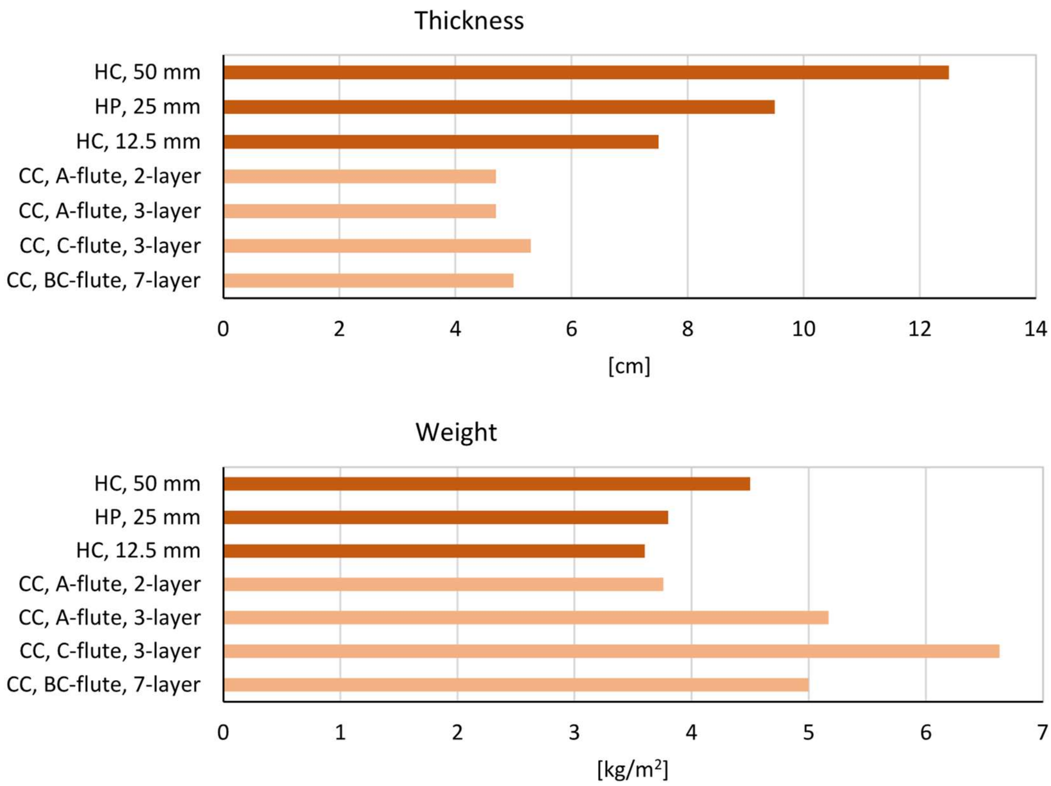


Figure 2.14. Thickness and weight of a homogenous panels with thermal resistance R = 1 m²K/W, made of paper-based materials.

Another important aspect of paper-based building products in terms of ecology is impregnation, lamination, bonding, and joining of the elements. When recycling is desired, it is crucial to maintain separable joints between the materials, which is often restricted in paper-based products, where bonding provides the most stable joints. In addition, impregnates and coatings that penetrate into the paper can also hinder the recycling process. On the other hand, the use of protective measures against external factors such as water, fire, and micro-organisms is absolutely necessary for the safety of the structure. Achieving the appropriate balance between durability and environmental impact is one of the most important challenges when designing with paper. Different approaches to this problem are suggested, including incorporating facing materials [48,169] or biodegradable impregnants [92].

LCA analysis compared to conventional building materials

Several Life Cycle Assessment analysis regarding the use of paper-based products as insulating material has already been conducted, however, the environmental impact of paper-based structural elements has not yet been analysed. In the study by Cekon et al. various types of honeycomb panels and corrugated cardboard were compared to polyurethane insulation (PIR), polystyrene (EPS) and mineral wool (MW) specimens with the same thermal resistance. All the paper-based samples presented slightly better results than MW and significantly better than PIR, however, worse than EPS, mostly due to its low weight [81].

A similar analysis was performed by Asdrubali et al. on corrugated cardboard. Two types of cardboard flutes (C and E) were covered in three variants of fibres – recycled, virgin, and mixed. The impact of E-flute cardboard was more than two times larger than the impact of a C-flute, due to higher material density and lower thermal resistance. In addition, a notable difference was observed between virgin and recycled fibres. The lowest impact was presented by C-flute, recycled fibre cardboard, which was slightly lower than the impact of rock wool and polystyrene [80].

On the other hand, Secchi et al. demonstrate that honeycomb panels can be an alternative to gypsum-dropped ceilings for acoustic absorption, providing a 10% reduction in energy demand and a 34% reduction in CO_2 emission [90].

It should be emphasized that all the works cited concern cradle-to-gate approach analyses that do not include usage, nor end of life stage. One of the biggest advantages of paper-based products is their recyclability. Thus, although in the production stage differences in the environmental impact between paper-based and conventional products are often not remarkable, it can be assumed that in cradle-to-cradle or cradle-to-grave approach the differences would be much more distinct.

2.2. Paper-based building envelopes [21]

Paper attracts architects' interest thanks to a rare combination of low cost and good environmental properties. Although the most commonly applied products in the construction industry are paper tubes, used as columns or truss elements, paper products are also useful in building envelope design. These materials are usually associated with temporary and emergency architecture, however, properly selected and protected paper-based products can also be used in the envelopes of longer-life-span buildings, acting as a main structural and insulative material.

Paper-based building envelopes can be composed of plane or linear elements with a structural and/or insulative function. Three main envelope typologies may be distinguished, depending on the configuration of the elements (see Figure 2.15). The most intuitive, and therefore the most popular are sandwich structures, in which one or multiple types of planar elements (e.g. corrugated cardboard or paperboard) are laminated together. Sandwich envelopes offer high durability and stability without thermal bridges, but are relatively heavy, difficult to disassemble or recycle and have high adhesive usage.

Linear components, such as paper tubes, can be used to form row structures, in which elements are placed one next to another, forming an envelope. A row structure often results in more efficient load-bearing material use, especially when elements are filled in with insulation, therefore envelopes may be lighter and thinner. On the other hand, thermal bridges often occur between linear components.

The embedded frame is traditionally used in wood-based and metal profile structures, where linear, load-bearing elements are arranged at set distances with spaces in between filled with non-structural insulation. Such structure allows for optimal material use, reduction in weight and adhesive consumption.

[21] Research from this subchapter has been published as a scientific article in Journal of Façade Design and Engineering [168].

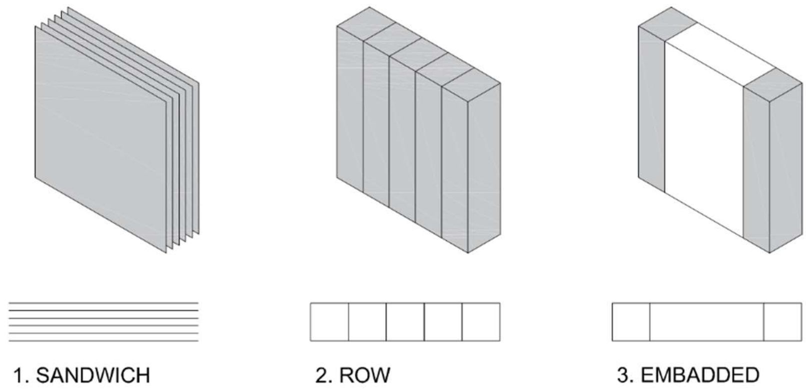


Figure 2.15. Types of paper-based envelopes' structure.

Paper-based building envelopes for the analysis were chosen from published projects and completed buildings, based on three criteria:

- the designed envelope consists of at least 70 % of paper-based materials (by volume) and cellulose fibre insulation is not the only paper material used;
- the envelopes provide noticeable thermal insulation (with U < 1 W/m2K);
- the building's expected lifespan is 3 years or more.

Ten different envelopes were chosen, including two constructed buildings, four prototypes and four theoretical, academic designs. The number of available case studies regarding paper-based envelopes with a set lifespan is very limited. The vast majority of paper architecture examples are temporary structures, pavilions and indoor elements. Although these case studies often present unique technical ideas, they do not provide thermal insulation nor protection against natural conditions, which are crucial for building envelopes. This subchapter covers all the case studies for which the available data allowed them to be analysed, therefore, the review can be considered comprehensive for the current state of the art.

2.2.1. Envelope case studies

Ten paper-based envelopes are described below in chronological order. Characteristic is on the materials used and their configuration, durability, and insulative properties of the presented designs

The envelope of Westborough Primary School

A semi-permanent social building for school children was designed by Cottrell and Vermeulen Architecture and Engineers Buro Happold (see Figure 2.16a). Built in 2001 in Westcliff-on-Sea, United Kingdom, it was the first permanent paper-based structure erected in Europe. Paper elements were used as the main building material to minimise the environmental impact of the building. A paper-based envelope (for both roof and walls) is mounted to the structure of paper tube columns and timber roof truss.

The envelope is composed of alternating layers of 50 mm thick paper honeycomb panels and 4 mm thick paperboard laminated together and fitted into timber frames, creating the insulative core with a total thickness of 167 mm. The internal surface of the envelope is covered with a polyethene pre-coated paperboard layer and an inflammable cellulose panel working as a pinboard. The external surface is ventilated to prevent water condensation inside panels and covered with a breather membrane and fibre-cement board [24,48]. Detailed information regarding the envelope is presented in Table 2.11 and Figure 2.19.

The building, with a declared lifespan of 20 years, and after small reparation of the roof was still in use in 2021. The chosen finishing materials provide very good protection against fire, water, and mechanical damage. It needs to be mentioned that the envelope insulative properties are rather low. As stated by the designers, it was not laboratory tested and U-value calculations were performed based on corrugated cardboard thermal conductivity [46]. However, as explained in previous subchapter, the insulative properties of honeycomb panels are significantly lower than for corrugated cardboard - thermal conductivity of 50 mm thick panel was measured as 0.125 W/mK [82]. Despite moderate thermal resistance, the envelope is relatively thick (231 mm) and heavy (41.62 kg/m^2) due to several layers of paperboard used.

Figure 2.16. Paper-based buildings: (a) Westborough Primary School building; (b) Wikkelhouse [22].

[22] Photos sources: (a) https://www.cv-arch.co.uk/westborough-cardboard-building/
(b) https://www.fictionfactory.nl/en/wikkelhouse/.

The envelope of Cardboard Dwelling in Brazil

A semi-permanent, cardboard-based residential building was designed in 2003 by Mirian Vaccari. The architect aimed to design housing for shanty towns reurbanisation in Sao Paulo, Brazil, however, they have never been constructed. Cardboard was chosen as an affordable and available material. The building structure is based on paper tubes and steel cable truss with cardboard-based envelope panels.

The envelope consists of two panels with an unventilated air cavity between them. Each panel is composed of a 25 mm thick paper honeycomb laminated with a 5 mm thick, A-flute corrugated cardboard layer on both sides. The external surface of the wall is protected with recycled drink cartons cladding (Tetra Pak - paper laminated with aluminium and polyethene film), and both internal and external surfaces are finished with an unspecified paint [170]. Detailed information regarding the envelope is presented in Table 2.12 and Figure 2.20.

Vaccari provides two unique design solutions - using recycled drink cartons and an unventilated air cavity. Reused Tetra Packs are watertight and beneficial from the environmental perspective, although the designer does not specify their assembly method, which might be difficult to implement in larger-scale production. Moreover, the inside surface of the panel has no protection against mechanical damage and both surfaces are flammable what negatively affects the safety of the structure. The wall core has low insulative properties, but due to the use of air cavity it is exceptionally light (6.18 kg.m^2), which also translates into low heat of combustion [23] (161.38 MJ/m^2).

CATSE walls

A series of paper-based walls for various applications was designed by Ozlem Ayan in 2009, based on findings of CATSE (Cardboard in Architectural Technology and Structural Engineering) research team from ETH Zurich. All of the walls, including the exterior, interior, structural and insulative ones were incorporated in a conceptual residential project, to present the suggested application. The structural, insulative external wall, type No 4, was chosen for the analysis, as the most relevant example.

[23] Heat of combustion was calculated in accordance with the materials' calorific values provided in EN 1991-1-2:2002 standard [171].

The unique element that connects all the Ayan's designs is a corrugated honeycomb core. The core is produced by laminating several layers of corrugated cardboard and cutting the obtained block into slices. The way the slices are arranged in the created core determines its insulative and mechanical properties. The discussed wall is composed of a 450 mm thick corrugated honeycomb core. Its internal surface is covered with steel facing or plywood. The external surface is ventilated and covered with steel facing and steel cladding or vapour barrier and wood cladding (the steel-finished variant was used in this comparison) [50]. Detailed information regarding the envelope is presented in Table 2.13 and Figure 2.21.

According to the designer, the wall has very high insulative properties (U = 0.12 W/m^{2}K), suitable to use even in passive buildings. Excellent thermal properties are reflected in the wall thickness (510 mm) and weight (78.74 kg/m^2). Steel finishing provides high resistance to water, fire and mechanical damage.

The envelope of Wikkelhouse

A prefabricated holiday house, designed by Rene Snel in 1996 and developed by Fiction Factory in 2012 in the Netherlands is the only commercial building in this analysis (see Figure 2.16b). The structure is composed of segments fabricated by wrapping and laminating corrugated cardboard around the house-shaped mould. In consequence, the whole envelope (walls, floor and roof) are composed of identical layers of materials. The segments, connected by steel rods placed in the cavities between the cardboard layers, provide both structure and insulation.

The envelope core is made of 24 layers of 2-layer A-flute corrugated cardboard, with a gap for joining and bracing elements in the middle. The prototype from 2012 was covered with a breather membrane and aluminium sheet on the outside and a kraftliner paperboard on the inside. However, the final product is finished with a breather membrane and wood cladding on the external surface and plywood on the internal surface. It can be assumed that wood is impregnated, although there is no information regarding the products used. Both variants of the envelope are ventilated, to avoid water condensation [45]. Detailed information regarding the envelope is presented in Table 2.14 and Figure 2.22.

According to the official Wikkelhouse website, over eighty houses have been sold by the end of 2020. The envelope provide good insulative properties (U = 0.35 W/m^{2}K) with moderate weight (27.84 kg/m^2). The original wrapping manufacturing method results in minimising the number of joints and potential thermal bridges. Used finishing materials provide sufficient resistance to water and mechanical damage, however, there is no data regarding fire protection.

The envelope of House of Cards

The temporary house shelter was designed by Jerzy Łątka and its prototype was built in 2016 in Wroclaw, Poland (see Figure 2.17a). The constructed unit is a part of a temporary housing project for refugees and homeless people. The whole design is paper-based, with paper L-shapes structural frames and paper wall and roof panels.

The building envelope consists of three layers of 50mm thick honeycomb panels laminated together and fitted into the frame made of paper T-shapes. External honeycomb panels were pre-coated with polyethene film on one side during production. Both surfaces of the envelope are finished with self-adhesive polyvinyl chloride foil. It was suggested by the designer that air cavities in the honeycomb panels could be filled with cellulose fibre to increase insulative properties [24]. Detailed information regarding the envelope is presented in Table 2.15 and Figure 2.23.

The envelope structure is very simple, which makes it easy to produce and recycle. The panels are exceptionally lightweight (5.83kg/m^2), which implies low heat of combustion (122.95 MJ/m^2). On the other hand, this lightweight structure does not provide sufficient thermal insulation, with U = 0.75W/m^2K. Although the foil-based finishing layer provides moderate protection against water, the surface remains flammable and prone to mechanical damage.

Figure 2.17. Paper-based buildings: (a) House of Cards prototype; (b) TECH 04 prototype [24].

The envelope of TECH 04

Transportable Emergency Cardboard House 4 is an temporary shelter designed by Jerzy Łątka and Agata Jasiołek, which prototype was built in 2018 in Wroclaw, Poland (see Figure 2.17b). The

[24] Photo (a) by J. Łątka.

facility was designed for refugees and victims of natural disasters. The modular design consists of cardboard-based sandwich panels bent at the construction site to form a one-element wall-roof-wall envelope. The timber structural elements are built-in the panels.

The envelope modules are composed of a double layer of 25 mm thick honeycomb panels laminated with four layers of 7 mm thick BC-flute corrugated cardboard on both sides. Panels are finished with varnish-coated aluminium sheets from the outside, and polyvinyl chloride self-adhesive foil from the inside [171]. Detailed information regarding the envelope is presented in Table 2.16 and Figure 2.24.

The design combines properties of both corrugated cardboard and honeycomb panels, which results in moderate insulative properties (U = 0.55W/m^{2}K) and low weight (9.91kg/m^2). Moreover, the lack of joints between roof and wall panels minimise the risk of thermal bridges, which improves the overall thermal performance of the structure. Aluminium cover, produced to be used as roofing, is watertight, incombustible and provides high resistance to mechanical damage.

The Tube Envelope

The envelope was designed by Agata Jasiołek in 2019 for the glass sorting plant located in Lębork, Poland, as a part of a thesis project supervised by Marcin Brzezicki. The project was not constructed, but the prototype of the single envelope panel was prepared. The designed production hall with the cross-laminated timber structure is covered with a paper-based envelope both from the side and from the top. The envelope panels are mounted to the grid timber structure.

The envelope core is composed of paper tubes arranged horizontally, one on top of the other. Each set of paper tubes is enclosed by a honeycomb panel, which forms a closed space around them, kind of box that is then filled with cellulose fibre. Consequently, paper tubes form an internal structure for blown-in insulation. The core is covered on both sides by a single layer of A-flute corrugated cardboard laminated with recycled polyethene film. Finishing panels consist of 3 mm thick paperboard laminated with watertight, PVC-covered textile, typically used for roofing and tents. Detailed information regarding the envelope is presented in Table 2.17 and Figure 2.25.

The Tube Envelope presents a different approach to the paper-based envelope design, incorporating a non-homogeneous layer of cellulose fibre with paper tube structure. Cellulose insulation is made of recycled newspapers, which is beneficial for environmental performance. Fibres provide efficient thermal insulation, however, the overall thermal properties of the envelope are affected by uneven heat flow through tube structure - small thermal bridges are formed where the tubes touch each other. The waterproof textile cover provides good protection against water without increasing the weight of the envelope. However, resistance to fire and mechanical damage is moderate.

Archicart Envelope

The emergency house-kit made of Archicart panels was designed and prototyped in 2019 by Dario Distefano and other researchers form Dicar University of Catania. The modular designs consist of prefabricated Archicart panels constructed in a patented PACO system, that form walls, roof and floor of the unit (see Figure 2.18a).

The PACO system panels are composed of rectangular tubes made of single layers of 1.4 mm thick corrugated cardboard, placed vertically one next to other. Each tube is filled with cellulose fibre insulation. Single panel consist of four or five tubes wrapped in external corrugated cardboard layer. The façade is protected by fire retardant PCV-coated textile stretched on an aluminium profile frame, while the internal surface remains unprotected [172]. Detailed information regarding the envelope is presented in Table 2.18 and Figure 2.26.

Figure 2.18. Paper-based buildings: (a) Archicart prototype; (b) Full Performance Paper House prototype [25].

The Archicart design cleverly uses the properties of corrugated cardboard, including its ability to be folded and formed in a spatial manner. The envelope is lightweight, yet provides high thermal insulation properties ($U = 0.22\ W/m^2K$) with limited thermal bridges. Moreover, the row structure limits the use of adhesives, reducing the envelope environmental impact. On the other

[25] Photo (a) source: https://www.archicart.com/prima-casa-di-cartone-ondulato/.

hand, aluminium frame of the external skin significantly increase both weight and environmental footprint of the design. The lack of indoor surface protection is another drawback.

Full Performance Paper House Envelope

The Full Performance Paper House (FPPH) is a prototype of temporary housing unit constructed at Technical University of Darmstadt (TU Darmstadt), Germany (see Figure 2.18b). It was developed within an interdisciplinary research group BAMP! (Building with Paper), composed of Rebecca Bach, Alexander Wolf, Martin Wilfinger, Nihat Kiziltoprak and Ulrich Knaack, with guest assistance of Jerzy Łątka.

The house is designed in a modular system and different configurations are possible due to the functional segments. The paper-based components are connected with a tongue and groove system and work as a load-bearing structure. The whole structure is covered with additional, waterproof cladding, that allows for envelope ventilation. The FPPH is produced by laminating multiple layers of various types of corrugated cardboard, paperboard, honeycomb and speciality papers. The core is protected by polyethene film and Tetra-pack cladding on the external surface [53,171]. Detailed information regarding the envelope is presented in Table 2.19 and Figure 2.27.

The sandwich-type envelope of FPPH is the heaviest of all the analysed designs, that's also associated with high heat of combustion. Unlike most paper-based walls, the FPPHE was laminated using adhesive based on styrene-butadiene rubber, which facilitates vacuum-press lamination, but increase environmental impact of the component.

Integrated Skeleton Façade

A series of paper-based building envelopes was designed by Rebecca Bach in her dissertation from 2021, including sandwich structures and paper tube skeleton located on the external surface of the envelope, internal surface or embedded. The last one (ISF) was chosen for this comparison, being the first example of embedded frame structure in paper-based building envelopes.

Each of Bach's envelopes consist of corrugated cardboard insulation and paperboard protective lavers. The ISF structure is made of rectangular paper tubes with internal dimensions of 100x100 mm and 10 mm thick wall, filled with cellulose fibre and embedded in corrugated cardboard BC-flute panel. Paper core is protected on both sides by 2 cm thick speciality paperboard panels and additional paperboard with acrylic paint coating on the external surface [173]. Detailed information regarding the envelope is presented in Table 2.20 and Figure 2.28.

The ISF design provides highest share of paper used for envelope composition and high thermal resistance without thermal bridges. The use of embedded frame optimises the consumption of loadbearing materials and allows for reduction in adhesive usage, as corrugated cardboard sheets are laminated only on points. Doubts can be raised about the use of thick solid cardboard panels that, while providing protection against fire, significantly increase the weight and combustion heat of the envelope. There is also no additional humidity protection in the internal surface.

Table 2.11. Westborough Primary School building and envelope characteristic.

Westborough Primary School			
Type of building		Social building for school children	
Authors		Cottrell and Vermeulen Architecture	
Date and location (if applicable)		2001, Westcliff-on-Sea, United Kingdom	
Envelope structure type		Sandwich	
Lifespan	20 years	Main materials	paper honeycomb, 50 mm thick, 3 layers paperboard, 4 mm thick, 4 layers paperboard precoated with PE film, 1 mm thick, 1 layer
Load-bearing	no		
Stage	built		
Ventilation	yes		
Weight [kg/m^2]	41.62	Internal surface protection technique	cellulose pinboard with fire retardant, 9 mm thick
Thickness [m]	0.23		
U [W/m^{2}K	0.72	External surface protection technique	breather membrane fibre-cement board, 8 mm thick
Heat of combustion [MJ/m^2]	549.73		

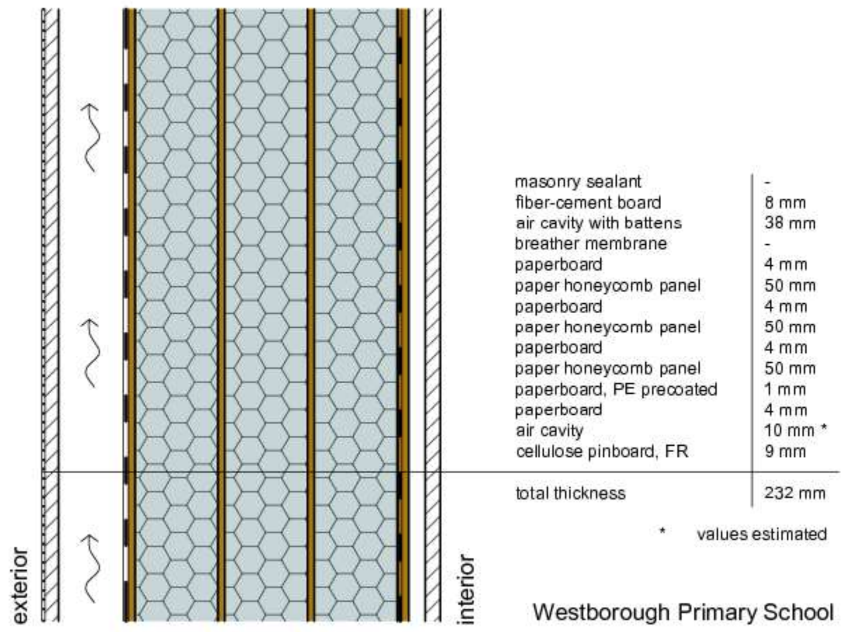


Figure 2.19. Westborough Primary School envelope section.

Table 2.12. Cardboard Dwelling building and envelope characteristic.

Cardboard Dwelling in Brazil			
Type of building		Residential building	
Author		Mirian Vaccari	
Date and location (if applicable)		2003, Sao Paulo, Brazil	
Envelope structure type		Sandwich	
Lifespan	semi-permanent, (unspec.)	Main materials	paper honeycomb, 25 mm thick, 2 layers corrugated cardboard, 3-layer, A-flute, 4 layers unventilated air layer
Load-bearing	no		
Stage	unbuilt		
Ventilation	no		
Weight [kg/m^2]	6.18	Internal surface protection technique	paint (unspecified)
Thickness [m]	0.10		
U [W/m^{2}K]	0.84	External surface protection technique	recycled drink cartons, paint (unspecified)
Heat of combustion [MJ/m^2]	161.38		

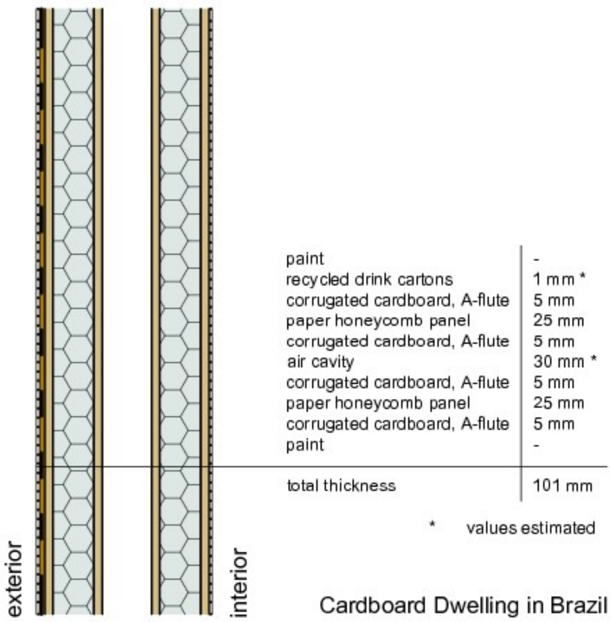


Figure 2.20. Cardboard Dwelling envelope section.

Table 2.13. CATSE building and wall characteristic.

CATSE wall No 4			
Type of building		Residential building	
Author		Ozlem Ayan	
Date and location (if applicable)		2009, no location	
Envelope structure type		Sandwich	
Lifespan	10 years	Main materials	Corrugated cardboard honeycomb panel
Load-bearing	yes		
Stage	unbuilt		
Ventilation	yes		
Weight [kg/m2]	78.74	Internal surface protection technique	plywood or steel sheet
Thickness [m]	0.51		
U [W/m2K]	0.12	External surface protection technique	steel facing with steel cladding or vapour barrier with wood cladding
Heat of combustion [MJ/m2]	960.60		

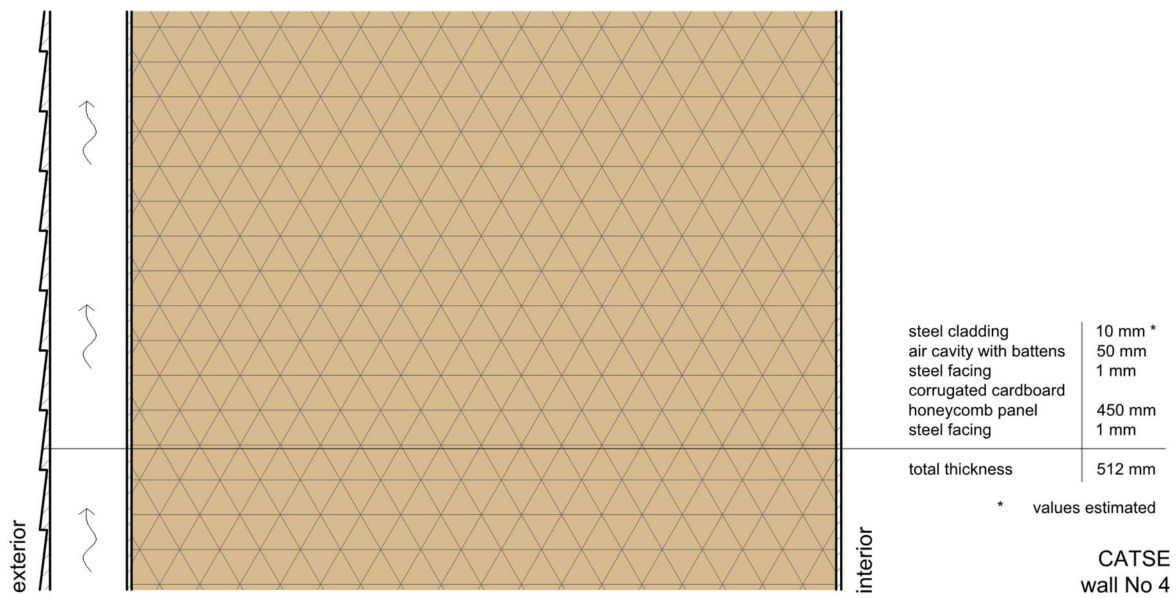


Figure 2.21. CATSE wall section.

Table 2.14. Wikkelhouse building and envelope characteristic.

Wikkelhouse			
Type of building		Holiday house	
Author		Rene Snel (inventor), developed by Fiction Factory	
Date and location (if applicable)		invented in 1996, developed and produced in 2012 in the Netherlands, no fixed location	
Envelope structure type		Sandwich	
Lifespan	50 years (15 years warranty)	Main materials	Corrugated cardboard, 2-layer, A-flute, 24 layers
Load-bearing	yes		
Stage	built		
Ventilation	yes		
Weight [kg/m2]	27.84	Internal surface protection technique	plywood
Thickness [m]	0.18		
U [W/m2K]	0.35	External surface protection technique	breather membrane wood cladding (aluminium sheet in the prototype)
Heat of combustion [MJ/m2]	518.85		

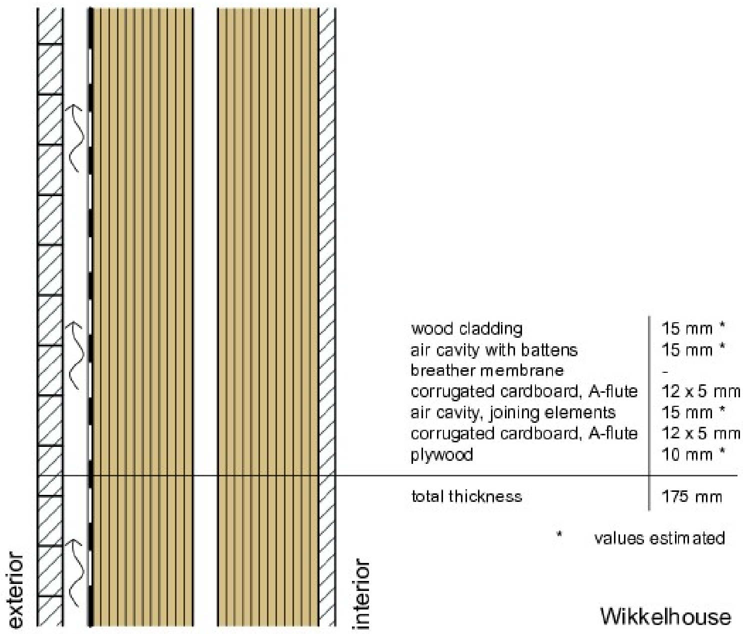


Figure 2.22. Wikkelhouse envelope section.

Table 2.15. House of Cards building and envelope characteristic.

House of Cards			
Type of building		Emergency housing	
Author		Jerzy Łątka	
Date and location (if applicable)		2016, Wroclaw, Poland	
Envelope structure type		Sandwich	
Lifespan	5 years	Main materials	paper honeycomb, 50 mm thick, 3 layers
Load-bearing	no		
Stage	built		
Ventilation	no		
Weight [kg/m^2]	5.83	Internal surface protection technique	PE film self-adhesive PVC foil
Thickness [m]	0.15		
U [W/m^{2}K]	0.75	External surface protection technique	PE film self-adhesive PVC foil
Heat of combustion [MJ/m^2]	122.95		

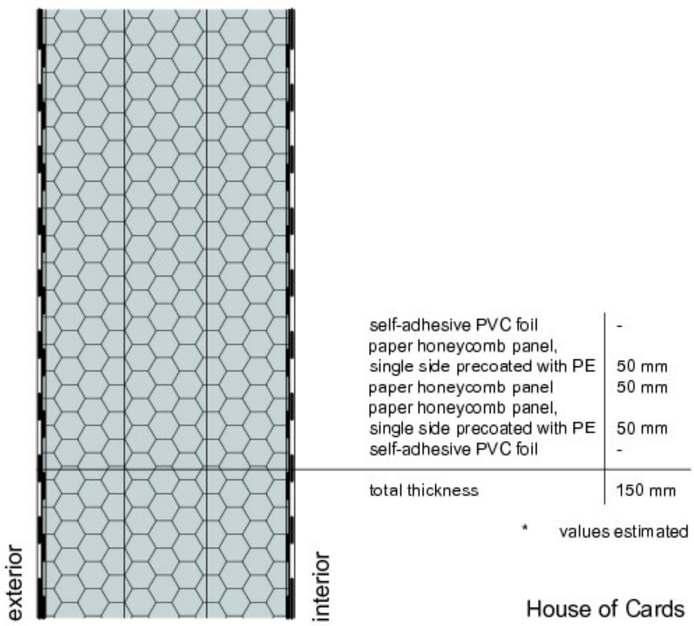


Figure 2.23. House of Cards envelope section.

Table 2.16. TECH 04 building and envelope characteristic.

TECH 04			
Type of building		Emergency housing	
Authors		Jerzy Łątka, Agata Jasiołek	
Date and location (if applicable)		2018, Wroclaw, Poland	
Envelope structure type		Sandwich / embadded	
Lifespan	5 years	Main materials	Corrugated cardboard, 7-layers, BC-flute, 8 layers paper honeycomb, 25 mm thick, 2 layers timber studs
Load-bearing	yes		
Stage	built		
Ventilation	no		
Weight [kg/m2]	9.91	Internal surface protection technique	self-adhesive PVC foil
Thickness [m]	0.11		
U [W/m2K]	0.55	External surface protection technique	aluminium sheet with protective paint coating, 0,6 mm thick
Heat of combustion [MJ/m^2]	172.35		

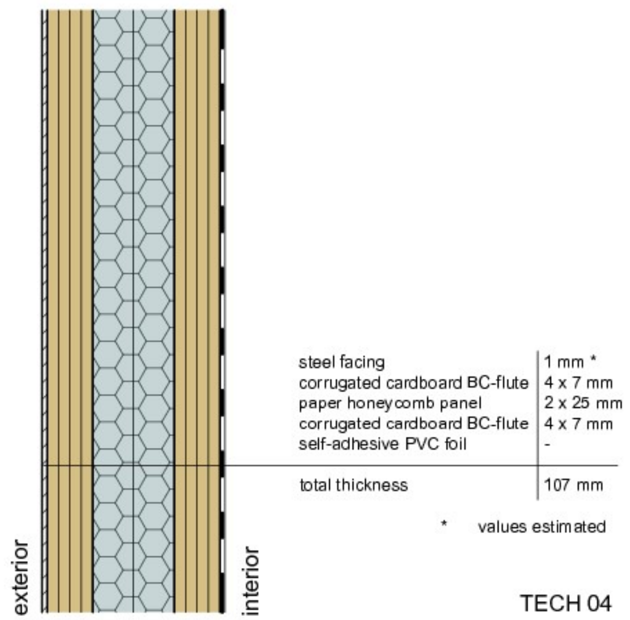


Figure 2.24. TECH 04 envelope section.

Table 2.17. Tube Envelope building and envelope characteristic.

Tube Envelope			
Type of building		Industrial building, glass sorting plant	
Author		Agata Jasiołek	
Date and location (if applicable)		2019, Lębork, Poland	
Envelope structure type		Row	
Lifespan	30 years (estimated)	Main materials	paper tubes, 4 mm thick, 177 mm diameter cellulose fibre, approx.. 170 mm thick layer paper honeycomb, 25 mm thick, 2 layers
Load-bearing	no		
Stage	unbuilt		
Ventilation	no		
Weight [kg/m^2]	29.93	Internal surface protection technique	recycled PE foil PVC-coated membrane
Thickness [m]	0.25		
U [W/m^{2}K]	0.33	External surface protection technique	recycled PE foil PVC-coated membrane
Heat of combustion [MJ/m^2]	630.45		

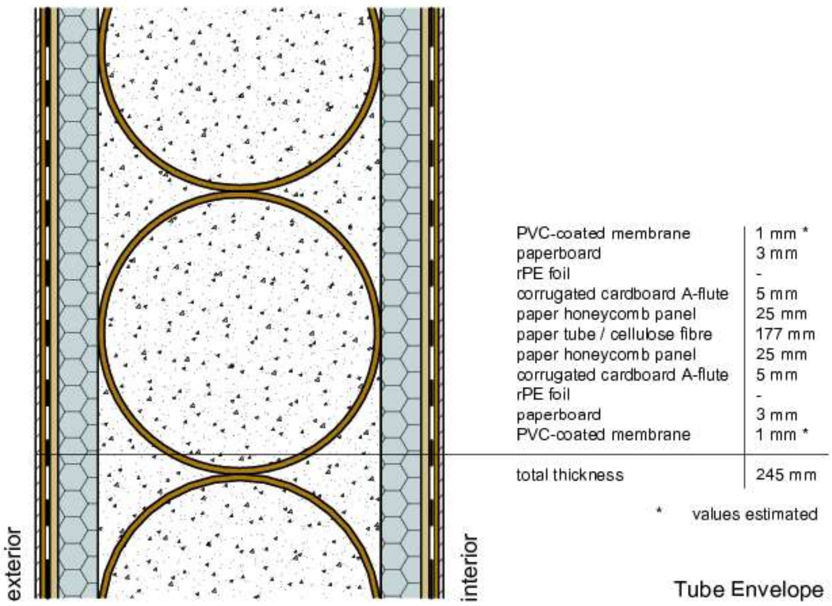


Figure 2.25. Tube Envelope section.

Table 2.18. Archicart Envelope building and envelope characteristic.

Archicart Envelope			
Type of building		Emergency housing	
Author		Dario L. Distefano	
Date and location (if applicable)		2019, Catania, Italy	
Envelope structure type		Row	
Lifespan	Semi-permanent	Main materials	Corrugated cardboard (1.4 mm thick), cellulose fibre
Load-bearing	yes		
Stage	prototype		
Ventilation	yes		
Weight [kg/m^2]	19.39	Internal surface protection technique	-
Thickness [cm]	30.05		
U [W/m^{2}K]	0.22	External surface protection technique	PVC-coated membrane
Heat of combustion [MJ/m^2]	283.86		

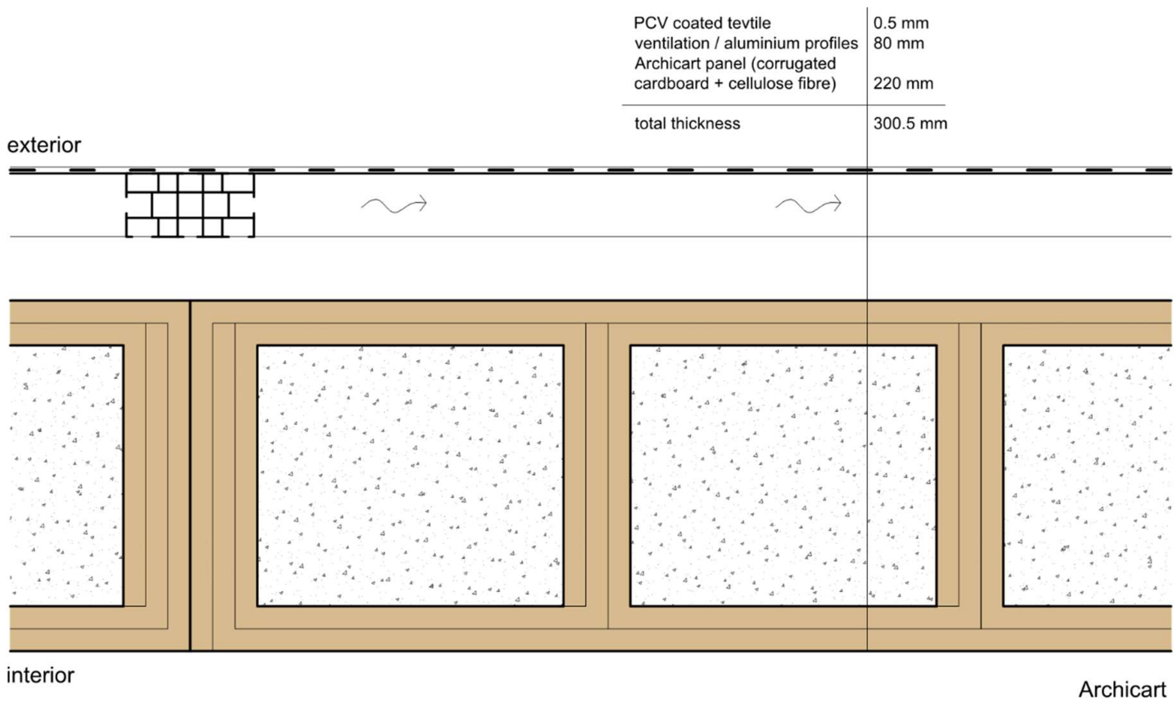


Figure 2.26. Archicart Envelope section.

Table 2.19. Full Performance Paper House building and envelope characteristic.

Full Performance Paper House			
Type of building		Temporary housing	
Author		BAMP! research team, TU Darmstadt	
Date and location (if applicable)		2020, Darmstadt, Germany	
Envelope structure type		Sandwich	
Lifespan	Min. 3 years	Main materials	Corrugated cardboard, BC flute Various types of paperboard and speciality papers Honeycomb panel 40 mm thick
Load-bearing	yes		
Stage	prototype		
Ventilation	yes		
Weight [kg/m²]	83.25	Internal surface protection technique	PE foil
Thickness [cm]	34.70		
U [W/m²K]	0.25	External surface protection technique	Tetra-pack coated paperboard cladding PE foil
Heat of combustion [MJ/m²]	1373.14		

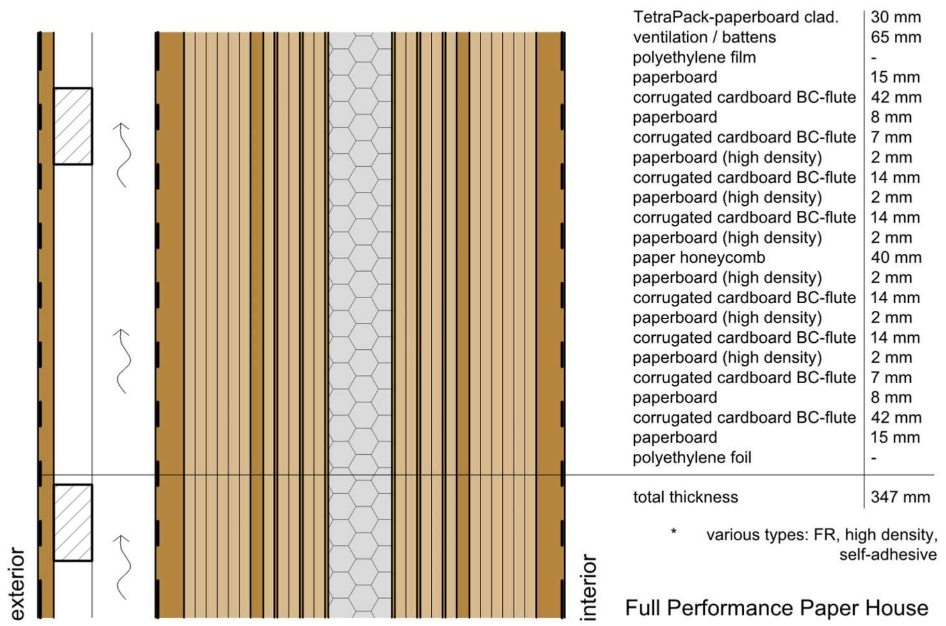


Figure 2.27. Full Performance Paper House Envelope section.

Table 2.20. Integrated Skeleton Facade characteristic.

Integrated Skeleton Facade			
Type of building		unspecified	
Author		Rebecca Bach	
Date and location (if applicable)		2021	
Envelope structure type		Embedded	
Lifespan	Unspec.	Main materials	Corrugated cardboard BC-flute Rectangular paper tubes 10 thick, 100x100 mm internal dimentions Paperboard Cellulose fibre
Load-bearing	yes		
Stage	unbuilt		
Ventilation	yes		
Weight [kg/m^2]	58.85	Internal surface protection technique	-
Thickness [cm]	30.00		
U [W/m^2K]	0.21	External surface protection technique	Acrylic paint
Heat of combustion [MJ/m^2]	938.32		

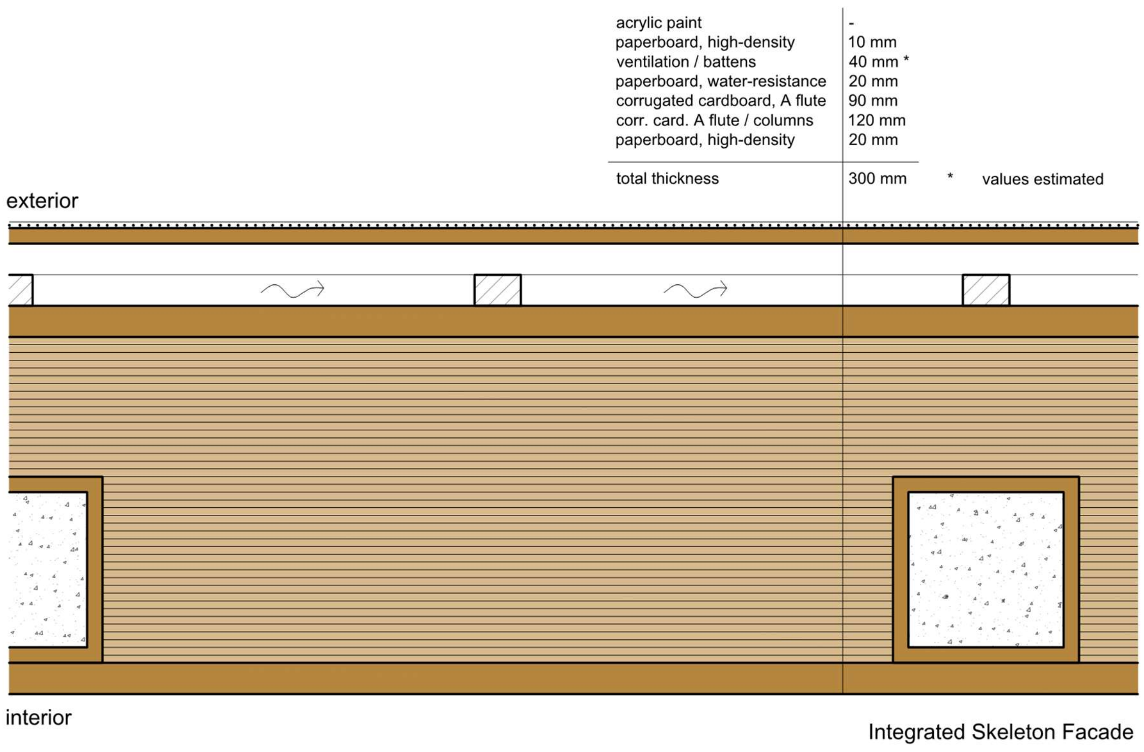


Figure 2.28. Integrated Skeleton Facade section.

2.2.2. Envelopes comparison

The envelopes discussed in the previous section present a variety of structures, material compositions, and characteristics. Nevertheless, certain tendencies and correlations among them can be identified. Detailed envelope properties comparison, which will be analysed in this section, can be found in Table 2.21 and Figure 2.29.

In the vast majority of cases, envelope panels are sandwich structures created by laminating together several layers of different materials. Furthermore, two row structures were described (one with vertical, and one with horizontal orientation), and only one embedded frame design. In all of these designs, the insulative core layer and finishing layers can be distinguished. The core layer, made of paper-based materials (honeycomb panels, corrugated cardboard, cellulose fibre) provides thermal insulation and structural stability, while the external layers protect the core from destructive factors. Non-paper materials, such as foil, metal sheets, wood, and fibre-cement board, are used for finishing layers.

There is a noticeable correlation between envelope thickness, weight, and thermal conductivity. An increase in the insulation properties always implies an increase in weight, while an increase in thickness is more variable, due to the use of different materials. The thickness of discussed envelopes differs from 10 cm in Cardboard Dwelling and 11 cm in TECH 04 up to 51 cm in CATSE. The weights range from 5.83 kg/m^2 in House of Cards and 6.18 kg/m^2 in Cardboard Dwelling, up to 78.74 kg/m^2 in CATSE and 83.25 in FPPH.

Thermal insulation properties are a key feature of the building envelope, from both the functional and environmental point of view. The analysed envelopes present thermal conductivity from 0.84 W/m^{2}K in Cardboard Dwelling up to 0.22 in Archicart, 0.21 in ISF and 0.12 W/m^{2}K in CATSE. Thus, CATSE is the only design insulative enough to meet the law requirements of Poland. However, in most cases, insulation deficits can be easily fixed by increasing the thickness of the partition.

Table 2.21a. Characteristics of paper-based envelopes.

		Westborough Primary School	**Cardboard Dwelling in Brazil**	**CATSE (wall No 4)**	**Wikkelhouse**	**House of Cards**
envelope structure type		sandwich	sandwich	sandwich	sandwich	sandwich
lifespan		20 years	unspec.	10 years	50 years	5 years
load-bearing		no	no	yes	yes	no
thickness [cm]		23	10	51	18	15
ventilation		yes	no	yes	yes	no
weight [kg/ m^2]		41.62	6.18	78.74	27.84	5.83
Heat of combustion [MJ/m^2]		549.73	161.38	960.60	518.85	122.95
U [W/m^2K]		0.72	0.84	0.12 [1]	0.35	0.75
Insulative core material		HP	HP, CC	CCH	CC	HP
internal surface	protection technique	FL, AM	VC	AM	AM (+ VC)	2x FL
	combustibility	non-combustible	combustible	non-combustible	combustible	combustible
	water resistance	medium	medium	watertight	medium	medium
	resistance to mechanical damage	medium	low	high	high	low
external surface	protection technique	FL, AM	FL, VC	2x AM	FL, AM (+ VC)	2x FL
	combustibility	non-combustible	combustible	non-combustible	combustible	combustible
	water resistance	watertight	high	watertight	high	medium
	resistance to mechanical damage	high	low	high	high	low

[1] value provided by the designer
abbreviations: HP – honeycomb panel, CC – corrugated cardboard, CCH – corrugated cardboard honeycomb panel, CF – cellulose fibre, FL – foil lamination, AM – additional material, VC – varnish coating

Table 2.21b. Characteristics of paper-based envelopes.

		TECH 04	**Tube envelope**	**Archicart**	**FPPF**	**ISF**
envelope structure type		sandwich / embedded	row	row	sandwich	embedded
lifespan		5 years	30 years	unspec.	min. 3 years	unspec.
load-bearing		no	no	yes	yes	yes
thickness [cm]		11.0	25.0	30.0	34.7	30.0
ventilation		no	no	yes	yes	yes
weight [kg/ m^2]		9.91	29.93	19.39	83.25	58.85
Heat of combustion [MJ/m^2]		172.35	630.45	283.86	1373.14	938.32
U [W/m^2K]		0.55	0.37	0.22	0.25	0.21
Insulative core material		HP, CC	CF	CC, CF	CC, HP	CC, CF
internal surface	protection technique	FL	FL, AM	-	FL	-
	combustibility	combustible	difficult to ignite	combustible	combustible	difficult to ignite
	water resistance	medium	watertight	low	medium	low
	resistance to mechanical damage	low	medium	low	medium	low
external surface	protection technique	AM (+ VC)	FL, AM	AM	FL	VC
	combustibility	non-combustible	difficult to ignite	difficult to ignite	combustible	difficult to ignite
	water resistance	watertight	watertight	watertight	medium	low
	resistance to mechanical damage	high	medium	medium	medium	low

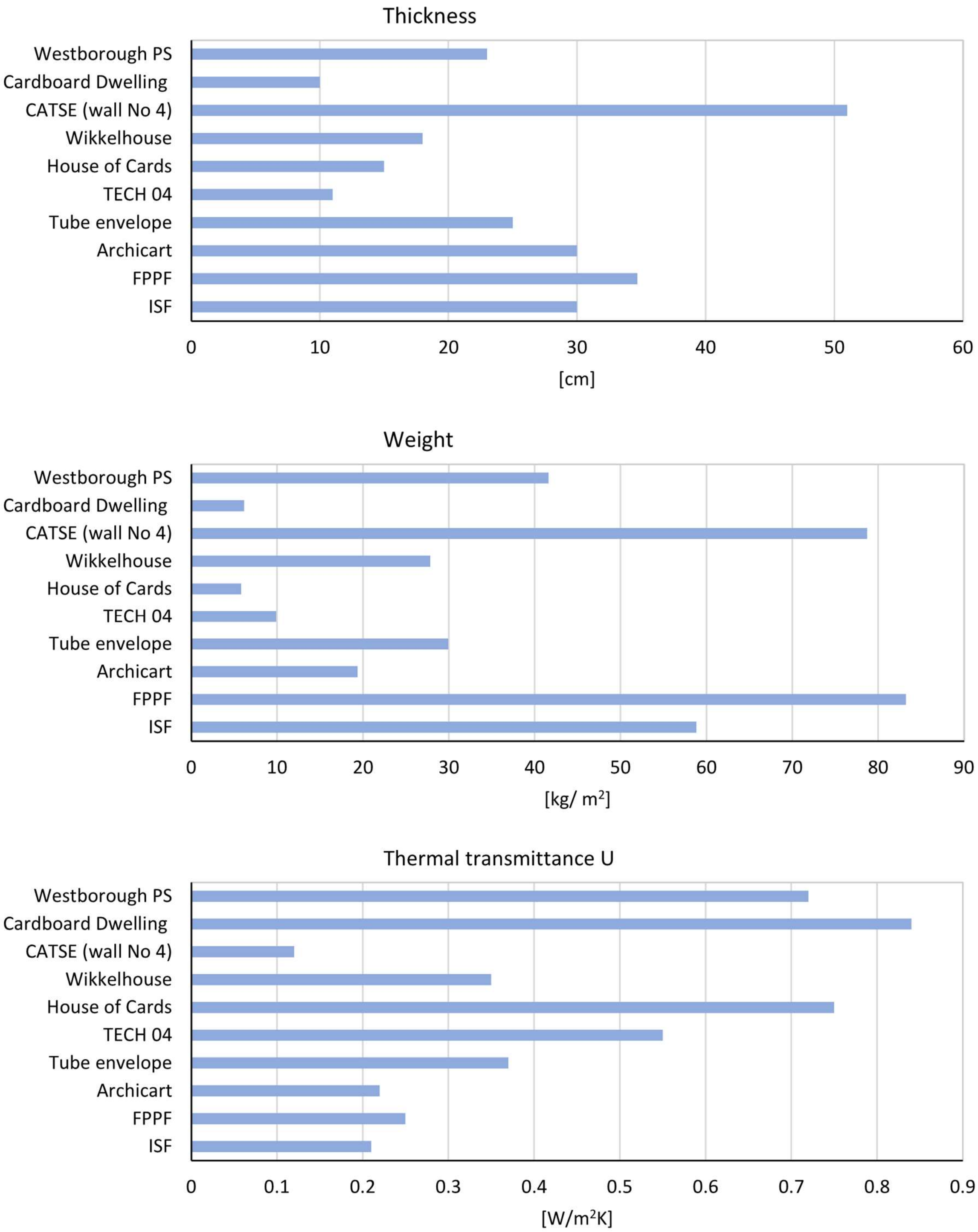


Figure 2.29. Selected properties of paper-based envelopes.

As paper is a fragile material, proper protection against water, fire, microbes, and mechanical damage is crucial for paper-based envelope functionality. Three main protective techniques can be distinguished: application of varnish coatings (VC), lamination with polymer films (FL), or incorporation of finishing layers made of additional materials (AM). Varnishes, films, and foils are affordable and easy to apply, thus they are usually used in temporary structures, however, they do not provide sufficient mechanical damage protection. Non-paper finishing materials, such as metal, plywood, or fibre-cement sheets are significantly more durable and, in some cases, fireproof, but they also increase the weight of the structure. Moreover, the envelope can be also protected by other elements of the structure preventing the surface of the envelope from direct contact with water, such as a large roof overhang. In the vast majority of the analysed envelopes, at least two different protection techniques are combined – the most common combination is lamination with additional material layers.

The highest water resistance was achieved in CATSE and Tube Envelope and the lowest– in House of Cards and ISF. Moreover, Westborough PS, TECH 04 and Archicart have watertight external surfaces, but weaker protection from the inside. The best surface resistance to fire is provided in Westborough PS and CATSE, as both sides of the envelopes are non-combustible. On the contrary, Cardboard Dwelling, and House of Cards have no fire resistance. CATSE and Wikkelhouse are the most resistant to mechanical damage, good resistance can be also observed in Westborough PS, while Cardboard Dwelling and House of Cards are the most vulnerable to damage. Considering all three destructive factors, CATSE wall can be recognized as the most surface durable design and the House of Cards envelope as the most fragile one.

Heat of combustion of the analysed envelopes (calculated in accordance with the materials' calorific values provided in EN 1991-1-2:2002 standard [174]) is between 122.95 MJ/m^2 for House of Cards and 161.38 MJ/m^2 for Cardboard Dwelling up to 960.60 MJ/m^2 for CATSE and 1373.14 for FPPH - it is correlated with the weight and thickness of the envelope. Furthermore, flammable layers of foils, polymer films and membranes increase the overall heat of combustion, in contrast to incombustible steel of fibre-cement finishing. It should also be noted that the density of the materials used affects their flammability. Products composed of thin layers of paper, such as corrugated cardboard, are easy to ignite, while dense paperboard layers may delay the penetration of fire into the core.

Most designers of the discussed envelopes indicate that low environmental impact was a fundamental reason for investigating paper as a building material for their work. Paper is widely recognized as an eco-friendly material, however, the actual environmental burden of the designed envelopes depends on additional factors, such as the share of recycled fibres in paper production, the type of adhesive or the possibility to separate and recycle individual row materials.

Chapter 3

Microscale – techniques

Comprehensive, interdisciplinary knowledge regarding the properties of paper components is required to design safe and efficient paper-based building envelopes. As presented in the State of the Art, various areas of this field have already been investigated. Although the quality of some works may be questioned, the general mechanical, thermal and acoustic properties of paper in the architectural context are known. On the contrary, impregnation and adhesive bonding techniques of paper-based building elements have not been investigated. Although research conducted for packaging and food industry may be useful to some extent, they do not translate directly into a building materials context.

Therefore, the research described in Chapter 3 aimed to fill these knowledge gaps in the areas of waterproofing impregnation, fire retardant impregnation and adhesive bonding. In each case, laboratory tests on paperboard specimens were conducted. A vast majority of impregnates and adhesives tested are designed to by applied on timber elements or other cellulosic materials and are already used in the construction industry.

3.1. Water and humidity impregnation [26]

To meet the safety and functional requirements, paper-based building elements need to be protected against the destructive effect of water and humidity. Protection can be provided by coating, lamination, waterproof outer layers or impregnation. Most impregnation methods have a negative impact on the environmental performance of the elements, however, this impact may be reduced when opting for biodegradable impregnating agents. This subchapter describes research that was conducted in order to determine the most effective techniques of impregnation, that may be used as part of water protecting system for paper-based building envelopes. Particular attention was given to biodegradable coatings, and several oil-based and wax-based wood impregnates were used. The specimens were tested for 24 hours in immersion and for 48 hours in high air humidity. As a result, the basic characteristic of the tested impregnation methods was established – water and water vapour absorption, deformation or delamination after immersion.

Research questions

Q1: How can paper-based building elements be protected against water and high air humidity?

Q2: Can biodegradable impregnates be an effective, sustainable alternative to synthetic varnishes?

[26] Research from this subchapter was conducted in the laboratories of WUST Faculty of Civil Engineering and has been published as a scientific article in International Journal of Sustainable Engineering [92].

3.1.1. Materials and methods

In order to ensure accurate and relevant test results, all specimens were prepared according to the following procedure. Two types of tests were conducted: to evaluate water absorption in immersion and humidity resistance of the impregnated specimens. For each test, an uncoated, control specimen and six specimens of each impregnation method were used: three oven-dried and three air-dried ones.

The tested impregnants were chosen from a variety of products used for wood impregnation in construction works and furniture manufacturing. Biodegradable impregnates based on both bio-based and synthetic oils and waxes or their combinations were selected. For comparison, the specimens covered with a conventional acrylic lacquer and emulsion wall paint were also tested. Finally, eight types of coatings were selected for testing, those were:

- linseed oil varnish (Dragon, Linseed oil varnish),
- wood wax – a mixture of beeswax, plant-based and synthetic waxes (ICA Poland, Colorit, Paste wood wax),
- wood oil – a mixture of natural oils with the addition of solvents and waxes (Rust-Oleum, Timberex, Hard wax oil),
- liquid paraffin (Aflofarm, Liquid paraffin),
- a mixture of linseed oil varnish and wood wax in a 1:1 weight ratio,
- layered linseed oil varnish (1 layer) and wood wax (1 layer),
- acrylic wood lacquer (PPG, Sigma Coatings, Sigmalife VS Acryl, Satin),
- emulsion wall paint with increased resistance to moisture (PPG, Bondex, Smart paint).

Specimens preparation

The tests were performed on rectangular 100×140 mm pieces of three-layer glued paperboard made of 100% recycled paper, with an area density of 1845 gsm (Zing, EskaBoard paperboard, 3 mm thick). Before the impregnation, all paperboards were conditioned at the temperature of 20°C and relative humidity of ~50%, for four days. 12 identical specimens for every impregnation technique were prepared (6 per test). Two layers of impregnates were applied using brush or microfiber cloth on both surfaces of each paperboard, and four layers were applied on the edges. The specimens were left to dry naturally at 20°C and ~50% RH. Half of the specimens were dried for four days, the other half after ten days of curing were dried in the oven at 50°C for 30 minutes.

Water-resistance test

The water absorption of the material can be measured in various ways, depending on the material type and application. The Cobb test is the most widely used technique for testing impregnated paper, especially for packaging materials (ISO 535:2014 [175]). However, it measures absorption in a very short period of time (60–180 seconds), which is not relevant for building-related applications. The testing method for this research was developed and modified by the author on the basis of techniques provided in standards ISO 29767, ISO 2812–2, ISO 5637 [176–178]. All the specimens were suspended from the rack in a vertical position and immersed in 18°C tap water up to 70% of their height, for 24 hours. The water uptake was monitored by weighing the specimens and measuring the thickness of the paperboard in the middle of each edge. The mass was obtained with an accuracy of 0.01 g and the thickness with an accuracy of 0.01 mm. To observe the change in water absorption over time specimens were weighted and measured several times during the immersion, as suggested by Buckley [179]. The specimens were controlled before the test and after 15 minutes, 1 hour, 3 hours and 24 hours of immersion. Before taking measurement the specimens were left to drain for 15 minutes at 20°C, ~50% RH. The specimens were re-immersed 30 minutes after being taken out of the water. The whole process of specimens preparation and testing is shown in Figure 3.1. After the test, the specimens were left to air-dry and observed for delamination and deformation. The obtained data was averaged and presented on graphs showing the increase in mass and thickness of the samples over time. Moreover, changes in the shape and structure of the specimens, their soaking patterns, deformation and delamination during the immersion and drying process were observed.

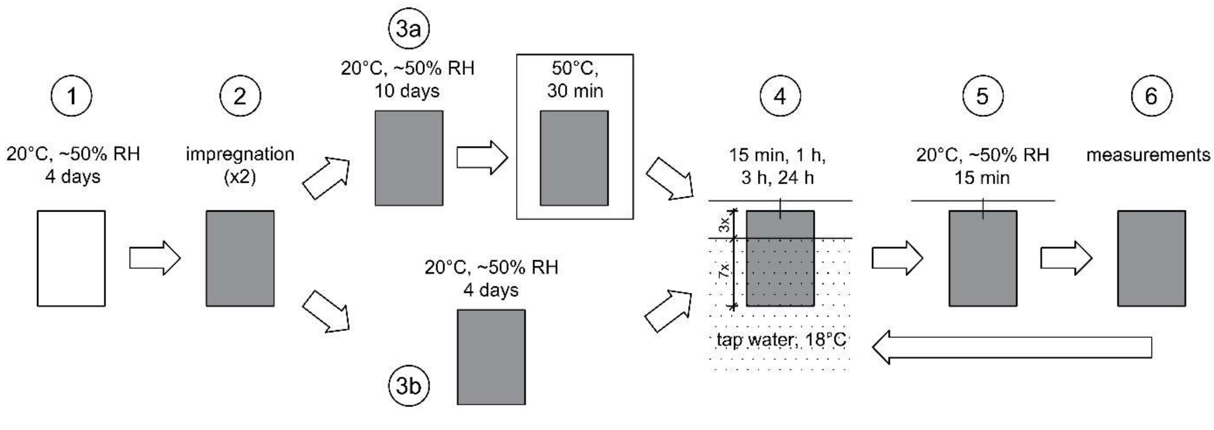


Figure 3.1. Scheme of specimens preparation and testing – water resistance test.

Humidity resistance test

A similar approach was applied to the humidity resistance test. All the specimens were exposed to conditions of 20°C and ~95% RH for 48 hours, by placing them in a closed container with a bottom filled with water. The water vapour uptake was monitored by weighing the samples with an accuracy of 0.01 g before the test, after 1 hour, 24 hours and 48 hours. The specimens were taken out of the container for 15 minutes for the measurements. The whole process of specimens preparation and testing is shown in Figure 3.2. The obtained data were averaged and presented on graphs showing the increase in the mass of samples over time.

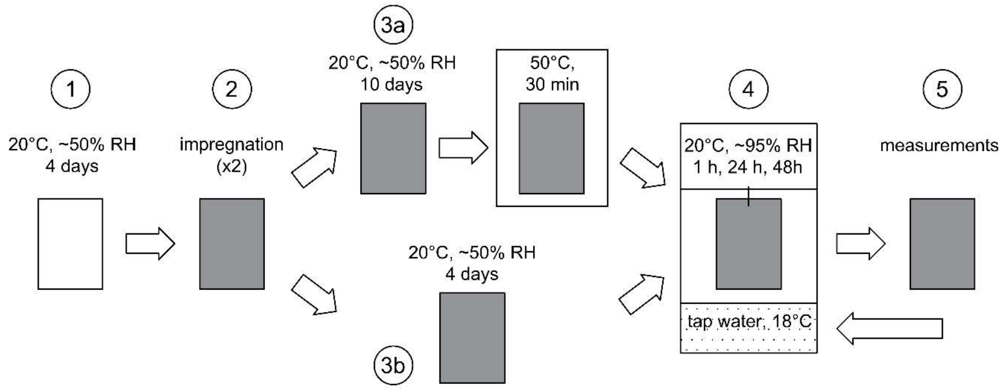


Figure 3.2. Scheme of specimens preparation and testing – humidity resistance test.

3.1.2. Results and Discussion

The detailed results, including water uptake during both tests and findings from samples observation, are presented in Table 3.1.

Results of the water-resistance test

Two types of extreme behaviour of the specimens during immersion can be distinguished:

- the constant, slow growth of weight (characteristic for acrylic lacquer)
- high absorption in the initial phase of the test, which decreases with time (characteristic for unimpregnated paperboard).

Also, significant differences are noticeable between oven-dried and air-dried specimens (see Figure 3.3). The fastest water uptake was observed in specimens impregnated with liquid paraffin and wood wax, while the biggest change in weight after 24 hours was measured in specimens covered with wood wax and the mixture of linseed oil varnish and wax. The lowest water uptake was observed in the specimens impregnated with acrylic lacquer and air-dried Timberex oil. Both combinations of linseed oil varnish with wood wax presented good water resistance in the first hour of immersion and significant water uptake in the first 3 hours. The oven-drying process has an extremely negative impact on the Timberex oil – the average water uptake in those specimens was 30.17 g, while in air-dried ones it was only 4.27 g. On the other hand, oven-dried linseed oil varnish specimens presented the third lowest water uptake in the test (21.44 g) and significantly better water resistance in the first 3 hours of immersion (2.78 g of water uptake) than the corresponding air-dried ones (18.48 g). The oven-drying process has also improved the water-resistant properties of the wall paint in the first 3 hours of immersion.

Table 3.1. Comparison of the effectiveness of the tested impregnants.

Type of coating and drying method (AD – air, OD – owen)		**Water absorption [g]**		**Water vapour absorption [g]**		**Delamination and deformation after immersion**	**Soaking pattern of immersed samples**
		after 15 min	after 24 h	after 1 h	after 48 h		
Uncoated	AD	32.35	38.81	0.42	2.08	complete delamination	whole surface and edges
	OD	33.57	38.05	0.40	2.59		
Linseed oil varnish	AD	1.86	26.90	0.12	2.07	no	whole surface and edges
	OD	0.69	21.44	0.12	2.41		
Wood wax	AD	9.99	37.59	0.06	0.98	complete delamination	edges and spots on the surface
	OD	0.95	34.64	0.07	1.44		
Hard wax wood oil	AD	0.09	**4.27**	0.06	1.20	slight delamination on the edges	edges and spots on the surface
	OD	0.22	30.17	0.05	1.48		
Liquid paraffin	AD	17.19	31.07	0.22	1.90	complete delamination	whole surface and edges
	OD	17.65	29.02	0.17	2.16		
Mixture of linseed oil and wax	AD	0.17	36.33	0.01	**0.48**	moderate deformation after drying	edges and spots on the surface
	OD	0.41	34.51	0.03	1.01		
Layered linseed oil and wax	AD	0.03	32.93	0.03	**0.74**	moderate deformation after drying	edges and spots on the surface
	OD	0.08	32.55	0.04	**0.76**		
Acrylic lacquer	AD	0.09	**5.29**	0.03	1.32	slight delamination on the edges	spots on the edges
	OD	0.58	**6.51**	0.10	1.66		
Emulsion paint	AD	0.92	30.50	0.09	1.67	slight delam. on the edges, moderate deform. after drying	spots on the edges
	OD	0.62	34.40	0.12	2.15		

The biggest change in the paperboard thickness was observed in paraffin impregnated specimens. The smallest dimension changes were observed in acrylic varnish ones, regardless of the used drying technique (see Figure 3.4). Analysing the changes in weight and thickness of the specimens, paperboard covered with air-dried Timberex oil and acrylic lacquer presented the highest resistance to water, and the absorption progressed steadily. Therefore these impregnates can be recommended to be used in building elements exposed to contact with water. On the other hand, both combinations of linseed oil varnish with wood wax can be suggested to be used when the contact of the component with water is of short duration.

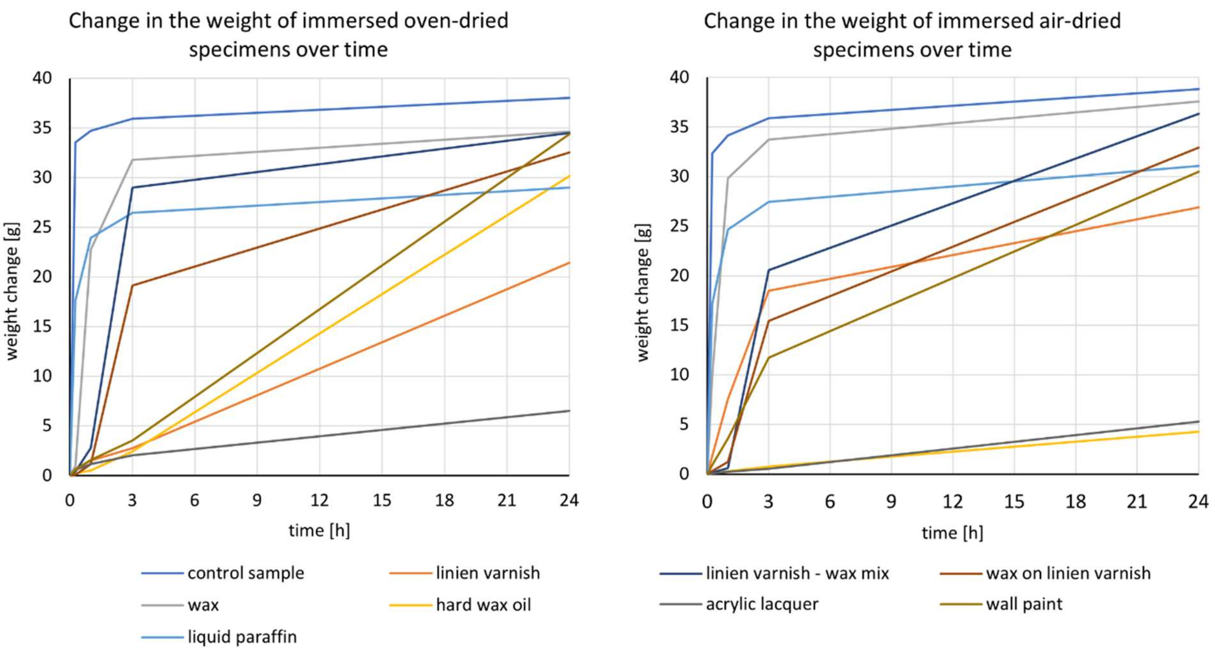


Figure 3.3. Change in the weight of immersed specimens over time; (a) oven-dried; (b) air-dried.

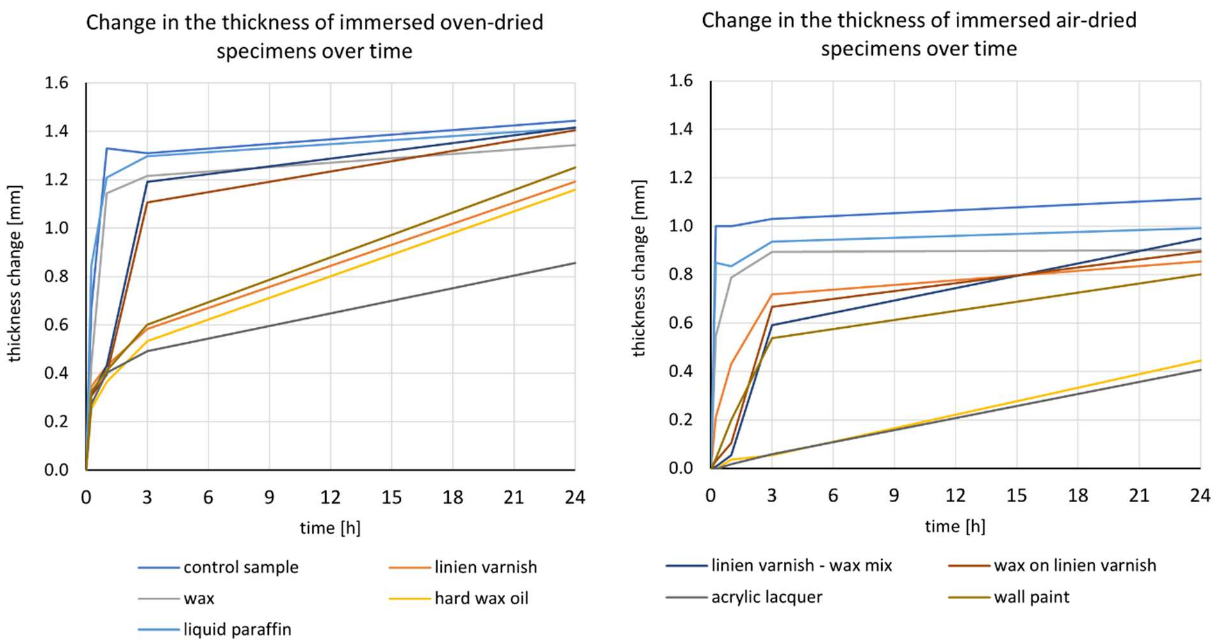


Figure 3.4. Change in the thickness of immersed parts specimens over time; (a) oven-dried; (b) air-dried.

The ability to maintain its shape and properties after the cycle of wetting and drying is crucial for paper applied in building materials, as any change in shape can disrupt the work of the building component. The specimens that delaminated in the shortest time were the ones impregnated with liquid paraffin – there was no significant difference between them and the unimpregnated paperboard. The only specimens which did not show any signs of delamination were the ones impregnated with linseed oil varnish. Moreover, when these specimens were completely dried after the test, they returned to their original form without showing any deformations. Also, the air-dried Timberex oil and acrylic lacquer impregnated specimens did not deform while drying.

In all cases, water uptake was the most intensive on the edges of the specimens. I the case of lacquer and paint-covered paperboards, soaking started on the edge and spread through the material. Specimens impregnated with linseed oil, paraffin, and wax, soaked on their entire surface, although there was a noticeably faster absorption of water at certain points, especially at the edges. The air-dried Timberex oil and acrylic lacquer specimens soaked only in spots. In the case of lacquer, the wet areas were located at the specimens edges. In the case of oil, the soaked areas were also in the centre area and their edges were softer and less precise (see Figure 3.5).

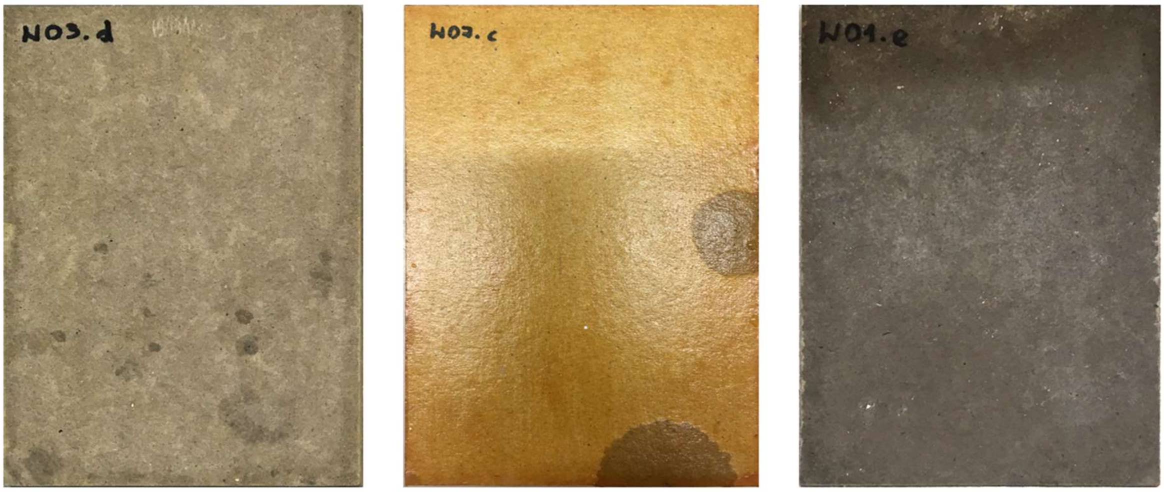


Figure 3.5. Water absorption patterns; (a) spots on entire surface, soft edges; (b) spots at the sides of specimen, sharp edges; (c) entire surface absorption.

The water absorption patterns showed, that regarding the impregnation technique used, the edges of paperboard are the most likely to absorb water, even though they were protected by a thicker layer of impregnates than the paperboard surfaces. Therefore, paper elements of building materials shall be designed in a way that minimises the contact of the paper edges with moisture. Also, it was observed, that coatings that form the protective layer on the surface of the specimens, without penetrating the paperboard (e.g. lacquer), are more prone to rapid soaking – water is quickly absorbed through every discontinuity of the coating. On the contrary, coatings that saturate the paper-board (e.g. linseed oil varnish) slow down the penetration of water into the material. All the observations and results discussed do not allow for indicating the one most efficient impregnation technique, however, they can help in selecting an appropriate method for paper-based products with a specific application. Factors such as the frequency and duration of contact with water or moisture, the type of paper, the component's function and shape should be taken into account when selecting a protective technique.

Results of the humidity resistance test

In contact with high air humidity, the highest mass increase was observed in the specimens impregnated with linseed oil varnish and liquid paraffin. The highest resistance to moisture was shown by the ones covered with combinations of linseed oil and wood wax. In the oven-dried specimens, the best results were obtained with layered impregnates and in the air- dried specimens – with the mixture of both substances (see Figs. 3.6). Overall, the oven-dried specimens show a slightly bigger water intake, which may be explained by their lower moisture content at the beginning of the test. It can be noticed, that the highest humidity resistance was shown by coatings containing waxes. This corresponds with the results of reducing paper water vapour permeability achieved by Jeong and Jo with beeswax [109] and by Khwaldia et al. with Carnauba wax [110].

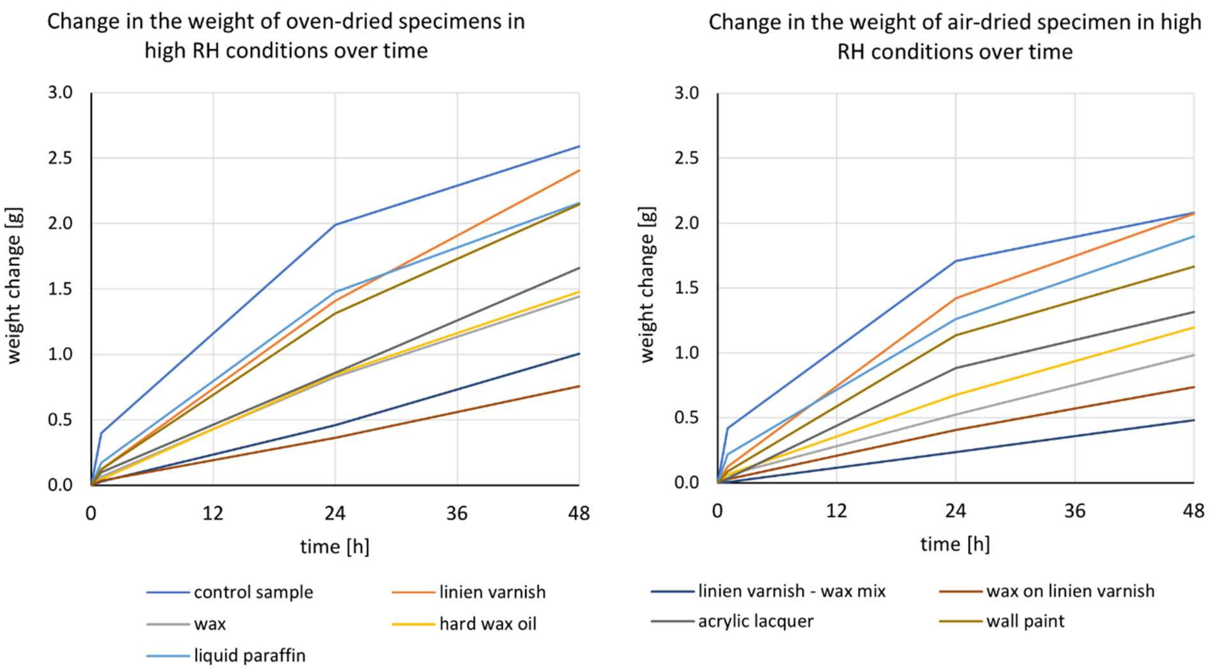


Figure 3.6. Change in the weight of oven-dried samples over time; (a) oven-dried; (b) air-dried.

3.1.3. Findings

The conducted research showed that biodegradable, oil-based and wax-based impregnates can provide protection against both water and humidity damages, comparable to the protection offered by conventional coatings such as acrylic lacquers. In both tests, the highest resistance was obtained by using composite oil-wax coatings. The effectiveness of these composite coatings is due to their complementary properties – waxes form a protective layer on the surface of the paperboard and oils saturate the paperboard, preventing water from penetrating the material. Moreover, linseed oil varnish presented unique properties in preventing the deformation and delamination of the paperboard. The tested impregnates can be a sustainable alternative to conventional protective varnishes and foils. However, it is unlikely that these impregnates will be the primary means of paper protection against water in the external parts of the buildings. Despite that, biodegradable impregnants can be used to protect the indoor elements of buildings and internal layers of the building envelope. They can also be used as an additional protective layer for external building elements, such as building facades, in combination with other cladding materials like metal sheets, wood cladding or fibre-cement panels, which should also provide necessary fire and mechanical damage protection.

Answers to research questions

Q1: How can paper-based building elements be protected against water and high air humidity?

A1: According to the conducted research, paper-based elements may be protected by impregnation, material additives during paper production, coatings, lamination or layering with waterproof material. The most efficient protection may be achieved by a combination of two or more of these techniques.

Q2: Can biodegradable impregnates be an effective, sustainable alternative to synthetic varnishes?

A2: The obtained results confirmed, that wax- and oil-based impregnating agents can form effective protection layers on paperboard. Complementary mixtures of waxes and oils provide protection comparable to acrylic varnish during immersion, and superior to them in hight humidity conditions. However, biodegradable impregnants do not provide sufficient water tightness to be used as a stand-alone protection technique for elements exposed to direct contact with water.

3.2. Fire impregnation [27]

Both fire and water protection are crucial for the safety and usability of paper-based products applied as building components. This subchapter investigates the possibility of combining environmentally-friendly fire retardants with oil-based and wax-based waterproofing coatings from the previous subchapter. The fire retardants selected, based on the State of the Art (section 2.1.7) were diammonium phosphate and a mixture of borax and boric acid in a 1:1 ratio. Single-flame ignitability tests were performed on the impregnated paperboard specimens to assess the fire performance of specimens with fire impregnation, waterproofing impregnation and both. The study has shown that the application of layered fire and waterproofing treatments on paperboard components is possible and leads to a significant reduction in flammability compared to untreated and only waterproofed specimens.

Research questions

Q1: How can paper-based building elements be protected against fire?

Q2: How to combine fire and water protection?

[27] Research from this subchapter has been published as a scientific article in Architecture, Civil Engineering, Environment [206].

3.2.1. Materials and Methods

The adopted methodology is based on single-flame material ignitibility test with specimens observation. The tests were conducted on rectangular 90×250 mm pieces of three-layer glued paperboard made of 100% recycled paper, with an area density of 1845 gsm (Zing, EskaBoard paperboard, 3 mm thick).

The raw materials for the preparation of the fire retardant (FR) solutions were obtained from Warchem Company, a local manufacturer of laboratory reagents from Poland. Three types of chemical compounds were used:

- borax (sodium borate - BX) – $Na_2B_4O_7$ x $10H_2O$;
- boric acid (BA) – H_3BO_3;
- diammonium phosphate (DP) – $(NH_4)_2HPO_4$.

Water impregnation techniques were selected based on research form previous subchapter regarding biodegradable paper impregnation [92]. Two types of coatings, that had presented the best performance in water-resistant tests were used in the presented research.

- A composite coating of linseed oil varnish (Dragon, Linseed oil varnish) and wood wax – a mixture of beeswax, plant-based and synthetic waxes (ICA Poland, Colorit, Paste wood wax);
- a homogenous layer of wood oil – a mixture of natural oils with the addition of solvents and waxes (Rust-Oleum, Timberex, Hard wax oil).

Specimens preparation

Four groups of paperboard specimens were tested:

- with only water impregnation (Group 1),
- with only fire impregnation (Group 2),
- with both types of impregnation (Group 3),
- control specimens of paperboard with no coating (Group 0).

For each type, three identical specimens were prepared. Two FR solutions were prepared by dissolving reagents in deionized water with a temperature of 50°C. The borates solution (BA-BX) was prepared from boric acid, borax and water in the ratio of 1:1:8, and phosphorates solution

(DP) from diammonium phosphorate and water in the ratio of 3:7. The concentrations chosen result from the solubility of the raw materials used.

Table 3.2. Types and designations of specimens.

Specimen designation	Fire retardant used	Waterproofing impregnant used
0-X-X	-	-
1-X-LW	-	linseed oil varnish + wood wax
1-X-O	-	wood oil
2-B-X	borax + boric acid (BA-BX)	-
2-DP-X	diammonium phosphorate (DP)	-
3-B-LW	borax + boric acid (BA-BX)	linseed oil varnish + wood wax
3-DP-LW	diammonium phosphorate (DP)	linseed oil varnish + wood wax
3-B-O	borax + boric acid (BA-BX)	wood oil
3-DP-O	diammonium phosphorate (DP)	wood oil

Designation code: group-FR intregantion-water impregnation.

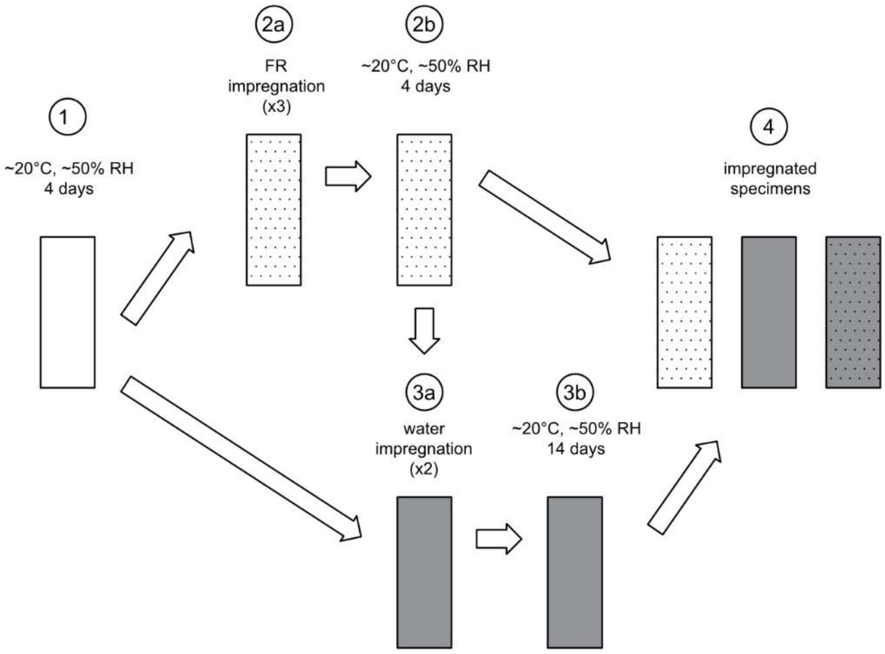


Figure 3.7. Specimens preparation process.

The impregnation was done manually, using a brush, on one surface of each specimen. Firstly, FR were applied in three layers and the specimens were air-dried for four days. The applied amounts allowed to achieve a saturation of approximately 200g/m^2 for DP and 167g/m^2 for BA-BX solutions. Secondly, the water impregnants were applied in two layers, and the specimens were conditioned for another 14 days in normal conditions (approx.. 20°C, 50%RH). Types of specimens are described in Table 3.2 and the impregnation process is illustrated in Figure 3.7.

Ignition tests and data analysis

The testing methodology was developed based on a single-flame source test described in ISO 11925-2 standard [180]. The tests were conducted in normal conditions (approx.. 20°C, 50%RH) with a standardized flame of the propane-butane burner, corresponding to the size of the match flame. The specimens were mounted in a frame, and the flame was applied to their impregnated surface at an angle of 45 degrees, 40 mm above the bottom edge of the specimen (see Figure 3.8). After 30 seconds of exposition, the flame was extinguished, and the specimen was observed for another 30 seconds. After 60 seconds from the start the test was finished and the fire was extinguished if necessary. During the tests, specimens were observed in terms of ignition, fire maintenance and flames reaching 150 mm above the fire application point.

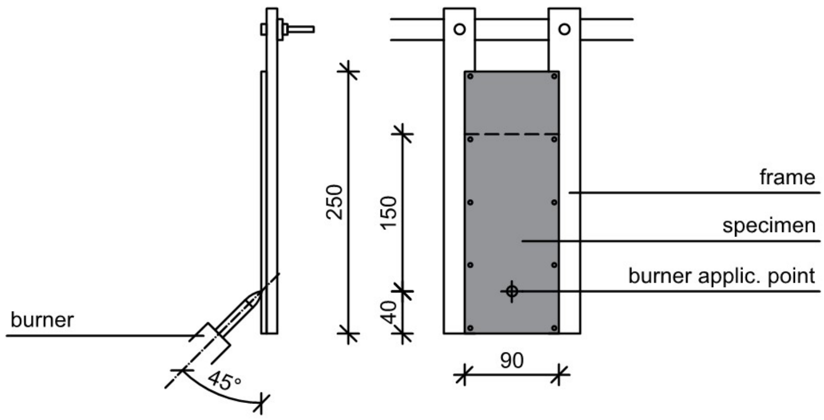


Figure 3.8. Ignition test setup.

After the test, specimens were photographed and the ImageJ software was used to analyse the shapes and calculate the areas of the charred surfaces. Lastly, the specimens were left for a year-long observation for changes in appearance, such as colour change, unintentional interaction between impregnates or possible crystallization of flame retardants on the surface of the specimen.

3.2.2. Results and Discussion

Significant differences in the ignition process of the four tested groups of specimens were noticed (see Table 3.3). The unimpregnated paperboards in Group 0 showed ignition and incandescence requiring extinguishing at the end of the test. These were the only specimens in which burning occurred through the entire thickness of the material. Specimens from Group 1 (only water impregnation) ignited and maintained the fire, which spread across the surface of the paperboard, resulting in the combustion of a large area. Specimens impregnated with a combination of linseed oil varnish and wax (1-X-LW) were the only ones with flames reaching the height of 15 cm, and the ones with the largest charred area. As expected, specimens from Group 2 (only FR) presented full fire resistance with no ignition and a uniformed, oval-shaped charred area.

In Group 3 specimens (both types of impregnation), a significant reduction in flammability was observed compared to Group 1 (only water impregnation), although the results were slightly worse than in Group 2 (only FR). None of the specimens maintained fire when the flame was removed, although a small ignition (not reaching a height of 15 cm) did occur for the phosphate-coated specimens (3-DP-O). The spread of the flames was noticeably smaller than in Group 1, which was also reflected in a limited charred area (see Figure 3.9).

Table 3.3. Results of the ignition test.

specimen	ignition	flame reaching 15 cm	maintaining the fire	Charred area [cm^2]
0-X-X	yes	no	yes	67.17
1-X-LW	yes	yes	yes	113.01
1-X-O	yes	no	yes	66.52
2-B-X	no	no	no	31.05
2-DP-X	no	no	no	45.71
3-B-LW	no	no	no	37.11
3-B-O	no	no	no	48.69
3-DP-LW	no	no	no	43.91
3-DP-O	yes	no	no	66.75

No problems during the impregnation process were observed – precoating with FR did not hinder water impregnation – and no changes in the appearance of the specimens occurred shortly after the impregnation. However, after the year-long exposure to light and changing air humidity, significant changes were noticed in some of the specimens (see Figure 3.10). On all of the paperboards impregnated with DP efflorescences are visible, while BA-BX specimens remain free from such changes. Moreover, all the specimens with water impregnation have developed a yellow tinge, that was especially visible on paperboards with wood oil treatment and DP precoating.

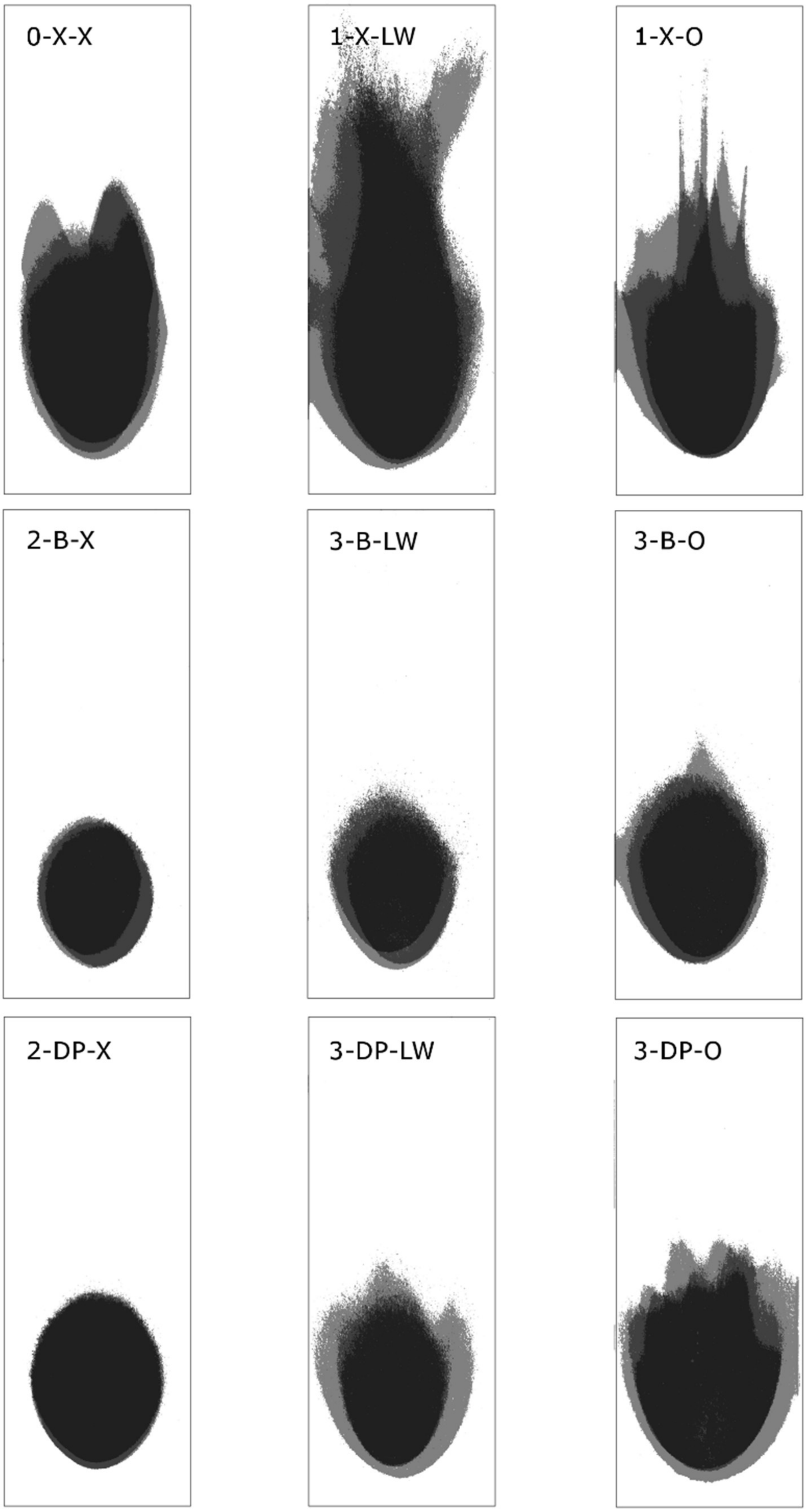


Figure 3.9. Charred areas on the tested specimens - superimposed images from three trials for each type.

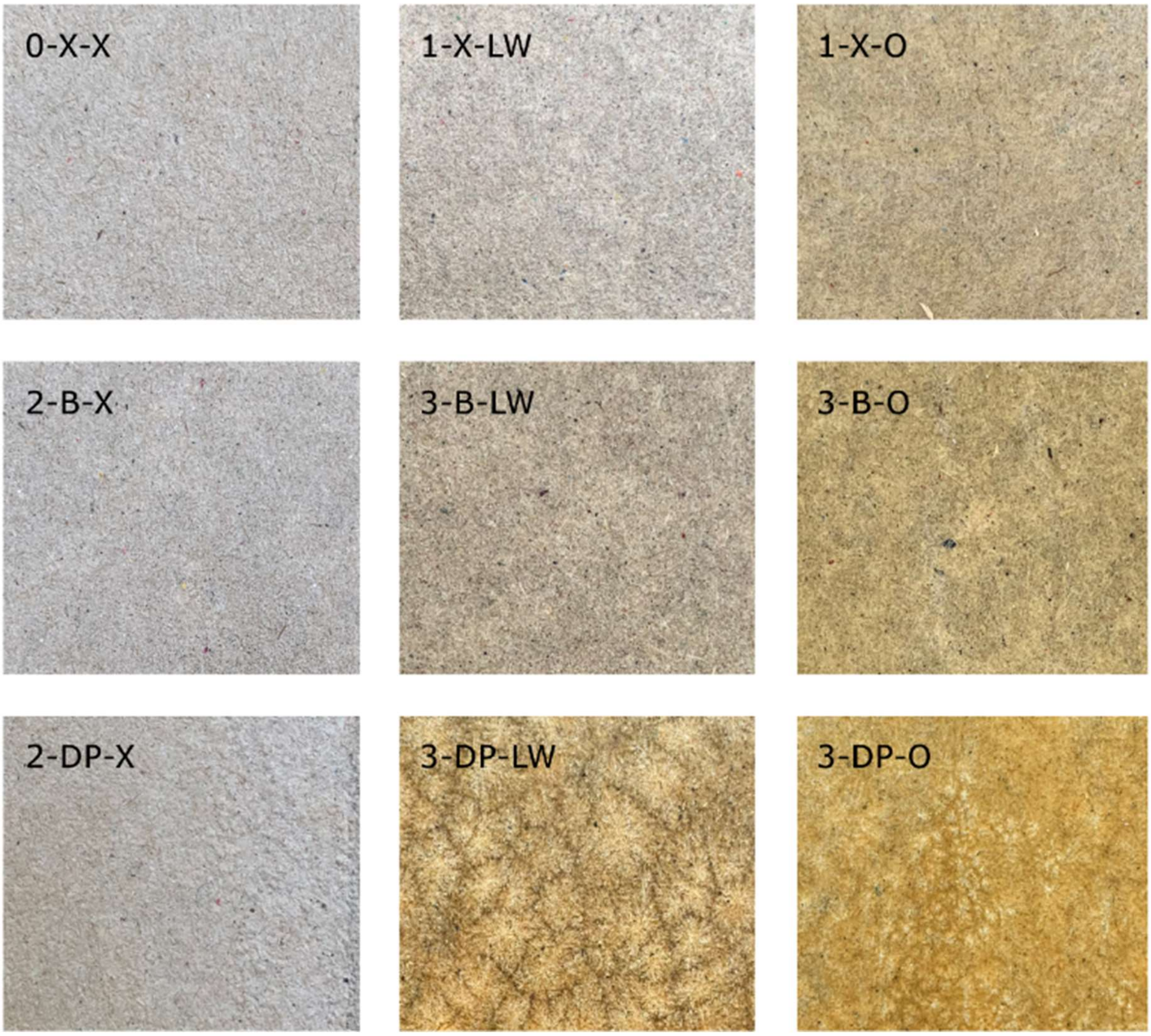


Figure 3.10. Surfaces of the specimens after a year-long observation period.

The results obtained, confirmed the validity of using inorganic FR while coating the paperboard with oil- and wax-based waterproofing agents. Coating of borates mixture was more effective in inhibiting ignition than diammonium phosphorate solution, and also more resistant to coating degradation over time. In the case of water impregnates, wood oil was less combustible than a mixture of linseed varnish and wax. The former, according to previous studies, is also more effective in protecting against water [92]. Therefore, on the basis of the data obtained, the best effect in terms of both water and fire protection and durability of the coating can be achieved by coating paperboard with a mixture of boric acid-borax and wood oil (testing specimen 3-B-O).

3.2.3. Findings

This subchapter described an environmentally-friendly technique of combined protective coating for paperboard – with boron and phosphorus compounds as fire retardants and biodegradable oil- and wax-based agents for water protection. Results obtained in ignitability tests confirmed the validity of this technique - precoating with flame retardant reduced the naturally high combustibility of oil-based impregnates and double-coated specimens showed a significant reduction in ignitability in comparison with uncoated ones. The use of a combination of borax and boric acid is recommended due to its high flame retardancy (despite the lower concentration of the fire retardant) and higher stability in changing air humidity.

The presented technique can be applied to building elements that require moderate water and fire protection, increasing their fire, microbes and mechanical resistance. It can also be used as additional protection between internal layers of the paper-based building envelope, hindering fire penetration into the material in case of fire. Furthermore, the incorporation of coatings may reduce the need of using finishing materials with a higher environmental burden (e.g. fire retardant plastic).

Answers to research questions

Q1: How can paper-based building elements be protected against fire?

A1: According to research conducted, paper-based building elements may be protected with fire retardant salts, e.g. borates or phosphorates, used as an additive in papermaking or impregnants applied to finished products. Additionally, paper can by protected with lamination or outer cladding made of FR materials. The most efficient protection may be achieved by a combination of two or more of these techniques.

Q2: How to combine fire and water protection?

A2: The obtained results confirmed, that it is possible to layer FR impregnation under waterproofing coating, reducing the combustibility of the obtained composite. Moreover, multifactorial protection may be achieved by a combination of impregnation, coatings and finishing layers made of non-paper materials. Finally, paper may be protected with a single layer of waterproof and fireproof material, such as a fibre-cement board or steel cladding.

3.3. Lamination [28]

Bonding is the widely used method of joining paper elements that provide the most stable connections. This subchapter evaluates the properties of commercially available adhesives that may be used for joining paper in architectural applications. The tensile tests were performed on single-lap specimens of paperboard bonded with various types and amounts of adhesives. Secondly, adhesives were assessed in terms of ease of application, environmental impact and mechanical strength.

Research questions

Q1: What types of adhesives should be used in paper elements lamination, considering joint strength and ease of handling?

Q2: Does the amount of adhesive used affect the joint strength of paper-based elements?

[28] Research from this section has been conducted during a research visit at Institute of Structural Mechanics and Design of TU Darmstadt, form May to July 2021.

3.3.1. Materials and Methods

The methodology adopted for the research combines both, mechanical tests, and adhesive performance assessment. Six different types of adhesives were examined, using various adhesive layer thicknesses. The results of single-lap tensile tests served as an input for final assessment of adhesives usability for paper-based building components.

The testing specimens were prepared using two types of three-layer paperboards and six different adhesives. The first paperboard was a white paperboard (WPB) manufactured for food packaging production with a thickness of 0.55 mm. It is composed of sulphate pulp skin layers and sulphate + CTMP (chemithermomechanical) pulp middle layer. The second material was brown, recycled-fibre paperboard (BPB) with a thickness of 1.45 mm. Six types of adhesives manufactured in Germany and Poland were used in this research, including polyvinyl acetate/polyvinyl alcohol woodworking adhesives (PVA), synthetic rubber upholstery glue (SRB) and dextrin-based adhesive for paper tubes winding (DX). Detailed information about products and manufacturers are presented in Table 3.4.

Table 3.4. Characteristics of evaluated adhesives.

	Manufacturer and product name	**Type of adhesive**	**Dynamic viscosity (mPas)**	**Solid content**	**pH**
1.	Ponal Classic HV710	PVA (polyvinyl acetate)	9 000 – 21 000	no data	6.5
2.	Leimwerk Holzleim D3	PVA (polyvinyl acetate)	10 000 – 16 000	51%	3.0
3.	Grünig 1041/224	PVA (polyvinyl acetate homopolymer and polyvinyl alcohol)	4 100 – 5 100	51%	4.0
4.	Grünig 1041/541 P	PVA (polyvinyl acetate and polyvinyl alcohol)	1 200 – 1 400	42%	4.0
5.	Fortis Bonatap M38 UN1133	SBR + SR (styrene-butadiene rubber and synthetic resins)	no data	36%	-
6.	Grünig 510/405	DX (dextrin, borax free)	1 500 – 1 700	66%	11.0

Specimens preparation

The single-lap specimens for tensile tests were prepared according to standard ISO 4587 [181]. For each type of specimen, two rectangular pieces of paperboard with dimensions of 100x300 mm were glued parallelly to its longer edge, with a 12.5 mm overlap length (see Figure 3.11). The amount of adhesive for each specimen was calculated based on the bonded area and required adhesive consumption, then measured using an electronic scale with an accuracy of ±0.01 g. There were four amounts of adhesives used in this work: 100, 150, 200 and 250 g/m^2. According to technical data sheets [182,183], the use of 150-200 g/m^2 adhesive is usually recommended, however, due to the bonding of non-conventional material, other amounts were also considered. For each type of paper and adhesive, two to three glue layers thicknesses were tested, depending on paper absorbency and adhesive density (see Table 3.5). Adhesive amounts that were not sufficient for uniform layer formation or caused glue leaking from between the paperboards were excluded. Additional pieces of paperboard were bonded at opposite ends of the specimens using the same gluing technique, to ensure that the force applied during the tensile test will be in the plane of the adhesive bond.

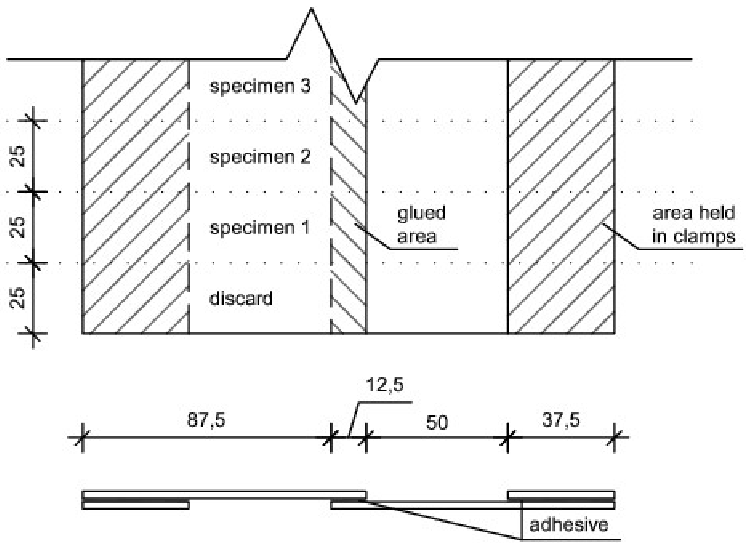


Figure 3.11. Specimens preparation.

The paperboard was preconditioned for five days at room temperature of 25°C ± 4°C and 50% ± 15% relative humidity and bonded in the same conditions. Afterwards, a uniformed pressure was applied on specimens' surface for 120 minutes and they were left to dry naturally for 7 days. Next, the specimens were cut into 25 mm wide pieces (see Figure 3.11) and conditioned in the testing conditions (23°C ± 1°C and 50% ± 5% RH) for three days. Before performing the tensile tests, specimens were weighed using an electronic scale with an accuracy of ±0.01 g and their thickness was measured in the centre of the glued area with an electronic calliper and accuracy of ±0.01 mm, to determine thickness and weight of the adhesive layer after curation.

Table 3.5. Types of specimens - amounts of adhesives used.

Type of paper			**BPB**			**WPB**			
Amount of glue (g/m^2)			150	200	250	100	150	200	250
No. and type of glue	1.	Ponal Classic HV710	x	x	x			x	x
	2.	Leimwerk Holzleim D3	x	x			x	x	
	3.	Grünig 1041/224	x	x		x	x		
	4.	Grünig 1041/541 P	x	x		x	x		
	5.	Fortis Bonatap M38 UN1133		x	x			x	x
	6.	Grünig 510/405	x	x	x		x	x	x

Tensile tests

Single-lap tensile tests were conducted on the prepared specimens according to the ISO 4587 standard [181]. Specimens were positioned in the tensile-testing machine with vacuum clamps and the machine was operated with a constant test speed of 1 mm per minute until joint fracture. For each type of specimen, five equal tests were performed. Testing time, displacement, maximum force, and type of failure were recorded. Afterwards, the destroyed specimens were photographed, and their adhesive surfaces were analysed for potential glue leakage and the presence of unbonded areas. Results were analysed for highest strengths and consistency of results across a group of one type of specimens. Results were considered consistent if (i) the force standard deviation for the group was no higher than 5% of the average failure force and (ii) unbonded areas were observed on no more than one specimen.

Adhesives assessment

The final assessment of adhesives for paperboard was conducted by comparing the ease of use and performance with mechanical strength. Based on data provided by manufacturers and authors experience with bonding paperboard with tested adhesives the Ease-of-Handling Score (EHS – method developed by the author) for each adhesive was calculated. EHS is a sum of scores in four categories: ease of application, efficiency, open time and environmental impact. Each adhesive was awarded from 0 (lowest score) to 2 points (best score) in every category. Secondly, the ease-of-handling score was juxtaposed with the average destructive force from tensile test of each adhesive.

3.3.2. Results and Discussion

Each adhesive and paper type allowed for preparation of specimens with two or three uniform adhesive layer thicknesses, without adhesive leakage. The SBR glue caused a significant difficulty in spreading evenly on the laminated surface, due to its high viscosity. On the contrary, the dextrin glue, with the lowest viscosity, required the most precise surface preparation, as even small irregularities significantly hindered the bond formation. After 7-days curation, the weight of PVA and SBR glues was reduced by approximately 50%, and the weight of the DX glue – by approx. 25%, due to evaporation of solvents. The thickness of the cured glue layer was between 0.09 and 0.31 mm.

Experimental results

The tensile tests were performed successfully on the all specimens. Fracture of bonded areas always involved paper tearing too (see Fig. 3.13). Depending on the specimen, failure occurred under forces in the range 215 to 459 N, (see Table 3.6 and Figure 3.12). The type of paper used in specimens' preparation had a clear impact of the specimens' performance – the WPB resulted in higher joint strength and significantly bigger displacements, due to high content of long, virgin cellulose fibres in the material. This implies that it is no pure adhesive fracture but since the adhesive is partially soaked into the paper, it is a combined fibre-adhesive-failure. Nevertheless, the relative results of the various adhesives were similar regardless of the paper used.

All tested PVA adhesives displayed similar results, with the highest forces among the tested adhesives (371-459 N) and fracture displacements from 0.95 to 1.56 mm. The performance of dextrin adhesives was slightly weaker, with forces from 326 to 407 N and fracture displacements between 0.79 and 1.32 mm. The consistency of the results was met for 46% of all the tested specimen types and for a minimum of one glue layer thickness for each water-based adhesive. On the contrary, the SBR glue showed a different behavior – due to the adhesive layer's compliance, the specimens displacement was larger and the forces smaller (between 215 and 390 N). Moreover, none of the specimens from this group met the results consistency requirement.

Table 3.6. Results of single-lap tensile tests.

No. and type of adhesive		type of paper	amount of adhesive [g/m²]	average displacement [mm]	average failure force [N]	force standard deviation
1	Ponal Classic HV710	BPB	150	0.95 ± 0.11	365.43 ± 38.69	11%
			200	1.08 ± 0.02	410.85 ± 10.73	3%
			250	1.12 ± 0.05	432.04 ± 16.96	4%
		WPB	200	1.56 ± 0.27	446.25 ± 44.03	10%
			250	1.43 ± 0.11	432.15 ± 22.91	5%
2	Leimwerk Holzleim D3	BPB	150	0.99 ± 0.05	401.04 ± 15.89	4%
			200	1.00 ± 0.09	412.54 ± 14.37	3%
		WPB	150	1.63 ± 0.19	453.16 ± 32.61	7%
			200	1.54 ± 0.06	442.25 ± 15.27	3%
3	Grünig 1041/224	BPB	150	1.05 ± 0.02	416.15 ± 7.51	2%
			200	0.97 ± 0.08	385.09 ± 24.39	6%
		WPB	100	1.23 ± 0.17	400.16 ± 33.86	8%
			150	1.44 ± 0.09	445.97 ± 14.99	3%
4	Grünig 1041/541 P	BPB	150	0.87 ± 0.08	370.83 ± 26.97	7%
			200	1.11 ± 0.04	451.25 ± 10.57	2%
		WPB	100	1.42 ± 0.11	441.75 ± 21.73	5%
			150	1.56 ± 0.20	492.17 ± 34.39	7%
5	Fortis Bonatap M38 UN1133	BPB	150	3.25 ± 0.61	215.26 ± 74.07	34%
			200	1.55 ± 0.25	379.76 ± 29.91	8%
			250	1.42 ± 0.24	376.33 ± 46.01	12%
		WPB	200	1.36 ± 0.27	283.29 ± 94.18	33%
			250	1.77 ± 0.13	351.51 ± 116.12	33%
6	Grünig 510/405	BPB	150	0.79 ± 0.06	326.13 ± 27.18	8%
			200	0.97 ± 0.03	404.66 ± 7.52	2%
			250	0.96 ± 0.10	383.33 ± 44.17	12%
		WPB	150	0.84 ± 0.22	296.21 ± 59.02	20%
			200	1.18 ± 0.07	399.74 ± 20.04	5%
			250	1.32 ± 0.07	407.24 ± 20.62	5%

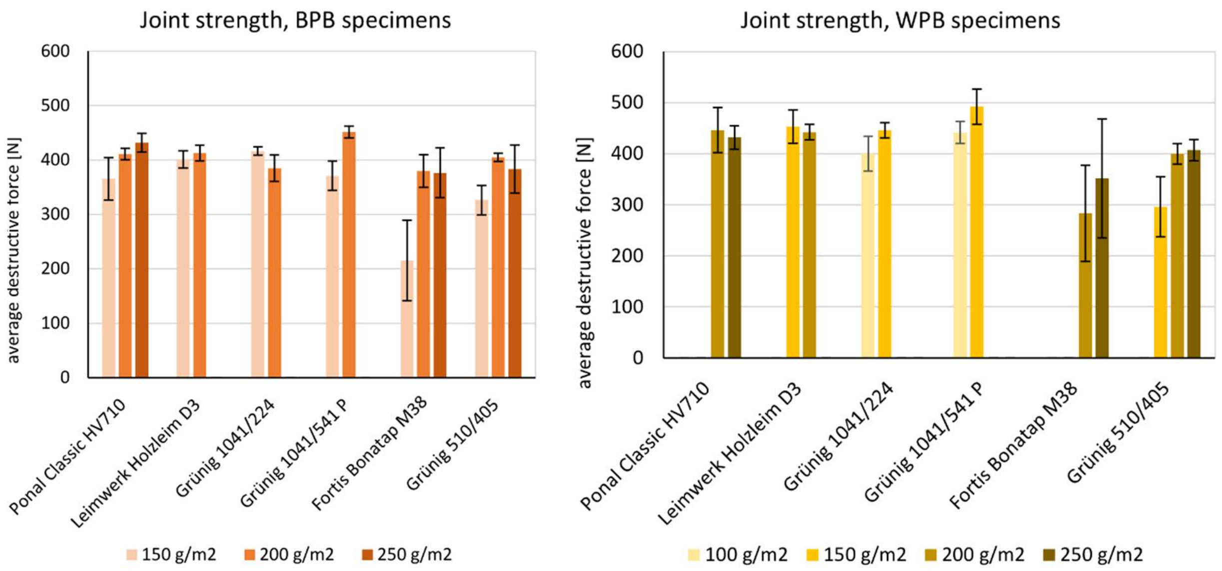


Figure 3.12. Results of tensile tests – average failure force for each type of specimens. Error bars represent one force standard deviation.

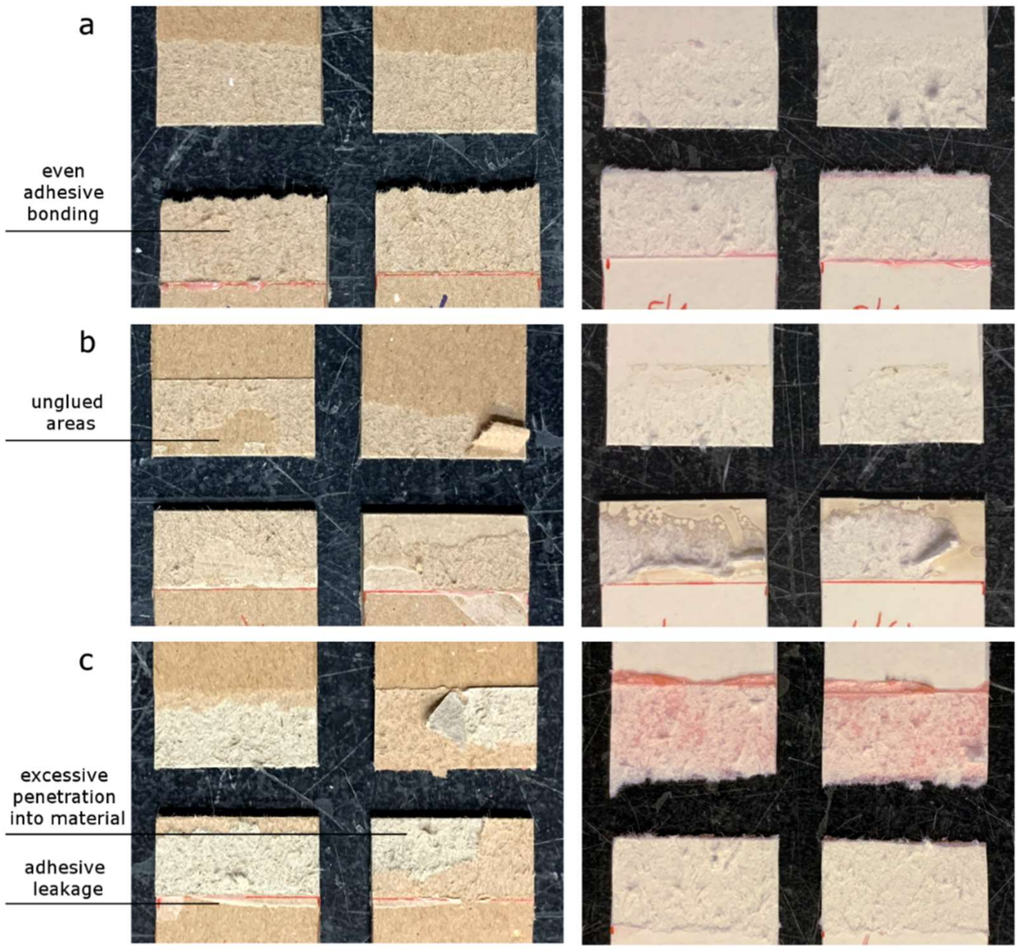


Figure 1.13. Examples of adhesive joints after tests: (a) adequate amount of adhesive; (b) insufficient amount of adhesive; (c) excessive amount of adhesive.

Adhesives assessment and application

The conducted experiment showed that both paper and adhesive type influence the adhesive joint strength. However, the adhesion strength should not be the only factor while choosing adhesive. Instead, aspects such as ease of application, level of water resistance, and environmental impact should be considered. Nevertheless, tensile tests allow for determination of the most effective adhesive layer thickness. It can be noticed, that an increase in the thickness of the adhesive layer negatively affects the bond strength. The highest strength was obtained in specimens with the thinnest layer sufficient to evenly cover and bond the surface. The increase of the adhesive thickness resulted in reduced consistency of results. Considering the limited strength of paper, it is the consistency of the results that should be the main criterion for the choice of adhesive parameters.

Table 3.7. Ease-of-handling metric for adhesives.

No and type of adhesive	**1**	**2**	**3**	**4**	**5**	**6**
	Ponal Classic HV710	**Leimwerk Holzleim D3**	**Grünig 1041/224**	**Grünig 1041/541 P**	**Fortis Bonatap M38**	**Grünig 510/405**
Ease of application	1	2	2	2	0	1
Efficiency	0	1	2	1	0	1
Open time	0	0	0	0	2	1
Environmental impact	1	1	1	1	0	2
Ease-of-Handling Score	**2**	**4**	**5**	**4**	**2**	**5**

5- highest performance, 0 – lowest perfomance

Based on the calculated Ease-of-Handling Score, adhesives #3 (Grünig 1041/224) and #6 (Grünig 510/405) presented the highest performance (see Table 3.7). When taking adhesive strength into consideration, adhesive #4 (Grünig 1041/541P) outperforms all others, however, adhesives #2 (Leimwerk Holzleim D3), #3 and #6 do also provide a good balance between ease of use and strength of connection (see Figure 3.14).

The results obtained with all water-based adhesives indicate their suitability for bonding paper-based building components. Although Grünig 1041/541P (adhesive #4) was assessed as generally the most optimal product, providing the strongest bond, it must be noted that differences in characteristics between various types of adhesives should be also considered regarding the specific application.

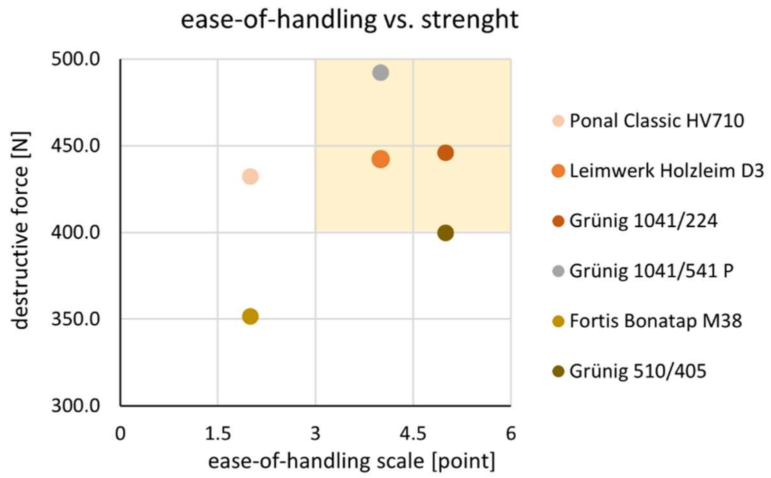


Figure 3.14. Adhesives usability assessment. Ease-of-handling vs. shear and peel strength.

Overall, PVA adhesives are the most universal solution for paper-based building elements bonding. These types of adhesives are easy to apply, have relatively low environmental impact and, depending on the additives, offer wide range of water-resistance levels. The most important disadvantage of PVA glues is short open time, that hinders large areas bonding. Therefore, PVA can be recommend for local bonding, e.g., in structural joints, or for machine application. On the other hand, dextrin glue offers good environmental properties and longer open time but provides slightly weaker joints and is water-soluble. Thus, dextrin-based adhesives can be recommended for lamination of larger area, nonstructural elements, e.g., cardboard layers of insulative panels, that are protected from humidity. A characteristic that may be especially important when bonding building components such as envelopes or façade elements is water vapor permeability. PVA glues significantly decrease permeability of bonded paper, while dextrin ones may even accelerate vapor penetration through material [173]. In consequence, the use of both types of adhesives in different layers of building component may facilitate its ventilation and decrease the risk of condensation inside the paper element. Due to limited strength and high environmental impact, the use of SBR glue is generally not recommended, unless a joint with low strength and especially high elasticity is needed.

3.3.3. Findings

The research conducted in this subchapter evaluated the performance of various types of adhesives that may be used for bonding paper-based elements in architectural applications. As a result, PVA (polyvinyl acetate and polyvinyl alcohol) adhesives may be recommended for general use, as the most efficient solution. However, the use of starch/dextrin adhesives should not be neglected, considering their environmental qualities. As adhesives play a key role in most paper-based structures, the suitable product should be chosen individually for each application considering factors such as the amount of stress on a joint, bonding technique, glued area, type of paper, lifespan of the element or exposure to moisture.

Answers to research questions

Q1: What types of adhesives should be used in paper elements lamination, considering joint strength and ease of handling?

A1: Various types of adhesives may be used for paper bonding, including water dispersions based on polyvinyl acetate, polyvinyl alcohol, starch or starch derivatives, resins (e.g. urea-formaldehyde or epoxy) and hot-melt adhesives (for example ethylene-vinyl acetate copolymer). Based on the conducted research, PVA adhesives may be recommended for general use, due to their versatility, availability and ease of handling. Furthermore, starch-based adhesives are suitable for environmentally-friendly bonding, when water resistance and high strength are not required.

Q2: Does the amount of adhesive used affect the joint strength of paper-based elements?

A2: According to the presented research, the amount of adhesive used significantly affects joint strength and behaviour. The highest joint strength was obtained in specimens with the thinnest layer sufficient to evenly cover and bond the surface. The increase in the adhesive thickness resulted in decreased joint strength and reduced consistency of the results. The amount od adhesive depends on paper and adhesive type and is usually higher for porous papers and thicker adhesives with high viscosity.

Chapter 4

Mesoscale – envelope layers

Lightweight building envelopes usually consist of three layers – thick, fragile core and thin, durable internal and external outer layers on both sides. In case of the self-supporting envelope which does not require assembly to other structural elements, core incorporates loadbearing components, providing structural stability, and thermal insulation, while outer layers offer protection against destructive factors, such as water, fire or mechanical damage. The envelope core is selected depending on the required insulation and load range, and outer layers – based on weather conditions, building life span and fire protection requirements. Therefore, for each building, a separate decision shall be taken regarding the core and both outer layers.

Based on the knowledge presented in the State of the Art, microscale research conducted in Chapter 3, the author's own experience in building with paper and prototyping process, six novel paper-based envelope cores were proposed, followed by fourteen outer layers suitable for indoor and outdoor application. Chapter 4 discusses the cores and outer layers of the paper-based envelopes separately, adopting environmental impact as the main assessment criterion.

4.1. Cores [29]

Paper-based materials, due to their availability, environmental benefits and high thermal properties, have already been implemented in several building envelope designs, as discussed in Chapter 2. However, most of them either did not optimise the use of the material or did not provide sufficient thermal insulation for use in permanent buildings. This subchapter proposes and analyses six original paper-based building envelope cores, suitable for use in permanent buildings in Poland, in terms of thermal and environmental efficiency. Proposals include cores with embedded paper tube structural elements, timber-cardboard studs and sandwich designs. The heat transfer coefficient of the envelopes was obtained via 2D computer simulations (ThermCAD software), and the environmental impact was assessed via LCA analysis, based on Ecoinvent 3.8 database. Paper-based cores were compared to standard SIP-panel[30] and timber frame walls.

Research questions

Q1: How can a structure of paper-based envelops be formed, to ensure structural stability and efficient material consumption?

Q2: How to thermally insulate building envelope with paper-based products, without compromising its environmental qualities?

[29] Research from this section has been published as a scientific article in Energy and Buildings [207] together with Paweł Noszczyk and Jerzy Łątka.

[30] Structural Insulated Panel – prefabricated sandwich panel, usually composed of two OSB boards with insulative core in between.

4.1.1. Envelope cores design

The analyses was performed on six paper-based building envelope cores. Aiming for a credible comparison of cores of similar functional parameters, the following design criteria were adopted.

- Each envelope should be a composite, self-supporting structure with load-bearing elements embedded in the layers of the envelope;
- the design should allow for prefabrication of panel elements assembled and connected on-site;
- the envelope shall allow additional protective finishing layers to be fixed to it on both sides;
- the main material of the envelope should be paper, with a minimum of 90% of the envelope volume made of paper-based products (corrugated cardboard, paperboard, honeycomb panels, paper tubes and shapes or cellulose fibre);
- timber and wood-based materials (e.g. plywood or OSB board) can be used locally, especially to facilitate elements connections;
- the thermal transmittance (U-value) of the core should range between 0.019 and 0.020 W/m^{2}K, to meet the Polish building code requirements for external walls in heated buildings, without additional insulative layers;
- the design should be material-efficient and should minimise the envelope impact on the natural environment – this is particularly important with regard to adhesives, which have a higher environmental burden than paper and may hinder recycling when overused.

Based on the adopted criteria, six envelope core designs were proposed, with three different types of structural elements. Characteristics of paper-based products incorporated in cores proposals are presented in Table 4.1, and properties of designed cores are presented in Table 4.2.

Envelopes 1A and 1B feature embedded frame structure with load-bearing studs composed of corrugated cardboard and timber-based elements. Boxes with cellulose fibres insulation are placed in between the studs (see Figure 4.1a). Envelope 1A is the lightest and thinnest of all the discussed designs.

Cores 2A and 2B are based on sandwich structural system, in which the load-bearing elements provide also insulation. The 2A envelope is composed of honeycomb sandwich panel with built-in paper tubes. To increase thermal insulation properties, a layer of triangle-shaped corrugated cardboard structure filled with cellulose fibre is added (see Figure 4.1a). Corrugated cardboard is the main component of the sandwich type 2B core, only locally strengthened with paper L-shapes and plywood (see Figure 4.1b). As a result, the 2B envelope is the heaviest of all the designs, surpassing them in weight by approximately three times. Emabdded frame cores 3A and 3B feature structural elements made of paper tubes filled with cellulose insulation. In both cores paper tubes are enclosed in other materials to form a rectangular column – honaycomb panels in 3A and cellulose-filled box in 3B. Boxes filled with unglued corrugated cardboard sheets are used as a thermal insulation in between columns (see Figure 4.1b).

Table 4.1. Parameters of paper-based materials used in cores design.

Material category	**Type/size**	**Thickness**	**Type of paper**
Honeycomb panel	14 mm cell	25 mm	Liner – 120 gsm, 100% recycled Core – 140gsm, 100% recycled
Honeycomb panel	14 mm cell	10 mm	Liner – 120 gsm, 100% recycled Core – 140gsm, 100% recycled
Corrugated cardboard	5-layers, BC-flute	6.1 mm	Liner - 110 and 100 gsm, flute – 95 gsm, 100% recycled
Paper tube	internal Ø 150 mm	8 mm (wall)	100% recycled
Paper L-shape	100x100 mm	10 mm (wall)	100% recycled
Paperboard	3-layered	3 mm	1845 gsm (total), 100% recycled

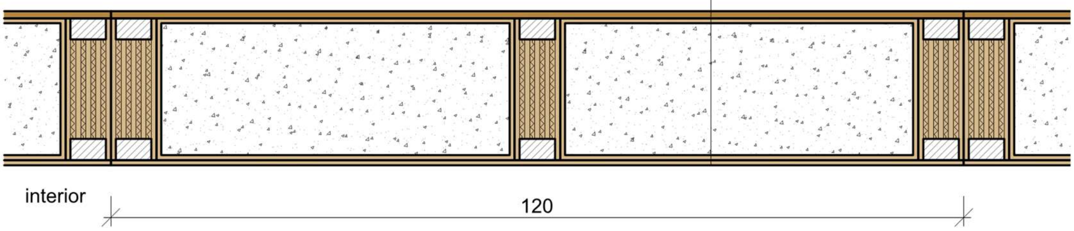
Table 4.2. General characteristics of research envelope cores.

Core No.	**Structural element**	**Main insulative material**	**Weight [kg/m²]**	**Thickness [mm]**	**Share of paper, by volume**
1A	corrugated cardboard with timber composite columns	Cellulose fibre	24.9	217	96%
1B	corrugated cardboard C-shape panels	Cellulose fibre, corrugated cardboard	30.3	240	96%
2A	Honeycomb panels composite with paper tubes	Cellulose fibre, honeycomb panels	32.9	318	97%
2B	Corrugated cardboard composite with L-shapes	Corrugated cardboard	97.0	269	99%
3A	Paper tubes	Corrugated cardboard	34.9	259	98%
3B	Paper tubes	Corrugated cardboard	31.9	265	99%

CORE 1A

paperboard corrugated cardboard BC, cellulose fibre filled boxes / columns corrugated cardboard BC x2, glued	10 200 7
total thickness	217 mm

exterior

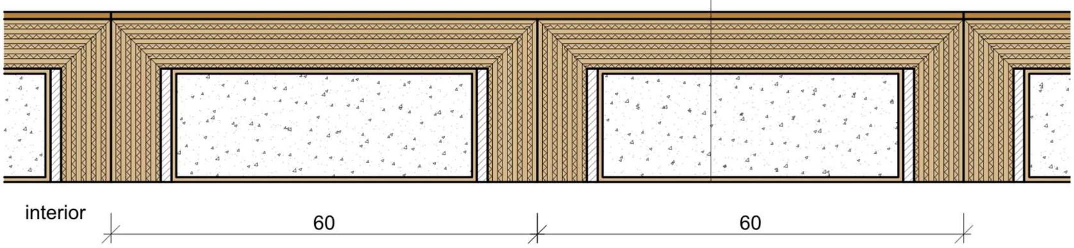


interior

CORE 1B

paperboard corrugated cardboard BC x10, glued corrugated cardboard BC, cellulose fibre filled boxes / columns	10 70 160
total thickness	240 mm

exterior

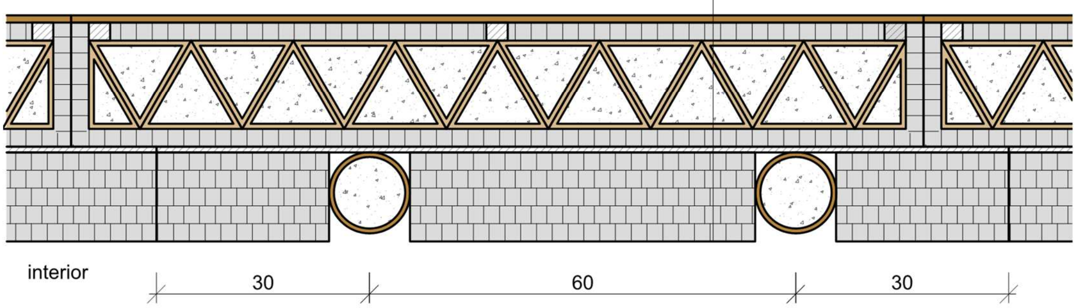


interior

CORE 2A

paperboard honeycomb panel 25 mm cellulose fibre / corrugated cardboard BC honeycomb panel 25 mm plywood honeycomb p. 25 mm x5, glued / columns	10 25 124 25 8 125
total thickness	318 mm

exterior



interior

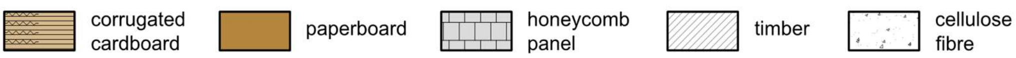
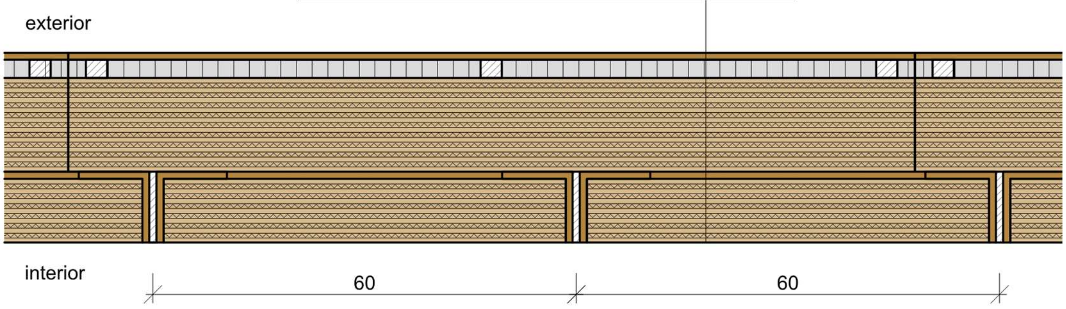


Figure 4.1a. Designed paper-based envelope cores.

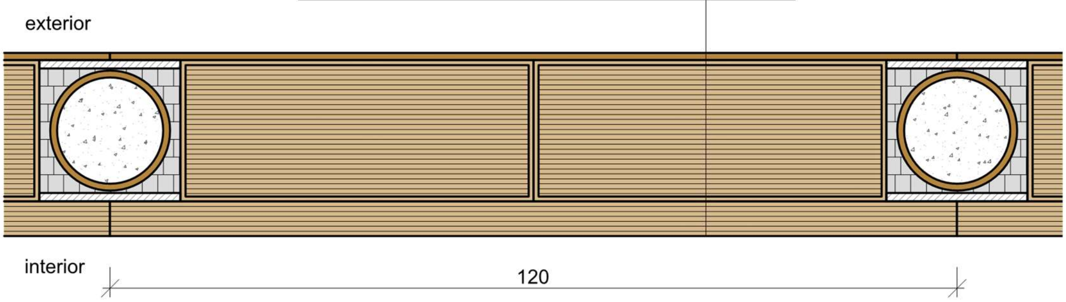
CORE 2B

paperboard honeycomb panel 25 mm corrugated cardboard BC x19, glued paperboard corrugated crdb. BC x13, glued / columns	10 25 133 10 91
total thickness	269 mm



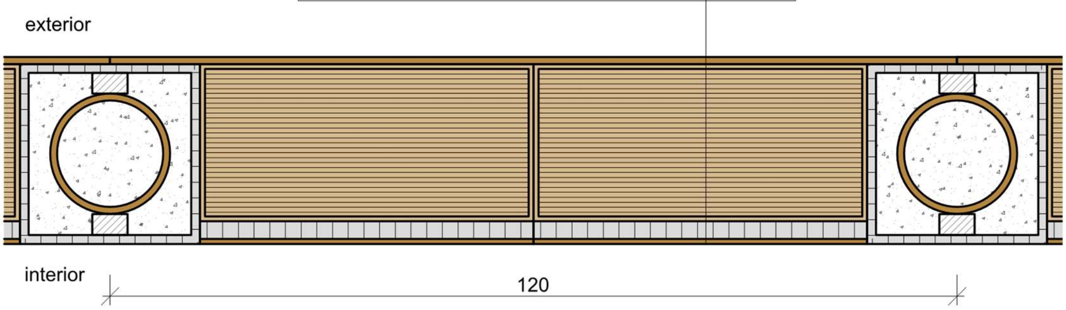
CORE 3A

paperboard corrugated cardboard BC box, filled with corrug. card. BC, unglued / columns corrugated cardboard BC x7, glued	10 200 49
total thickness	259 mm



CORE 3B

paperboard corrugated cardboard BC box, filled with corrug. card. BC, unglued / columns honeycomb panel 25 mm paperboard	10 223 25 7
total thickness	265 mm



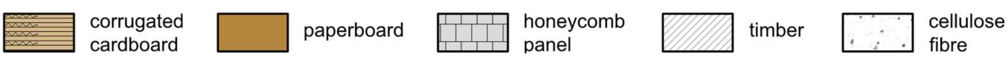


Figure 4.1b. Designed paper-based envelope cores.

4.1.2. Methods

The adopted methodology is composed of numerical thermal analysis and comparative Life Cycle Assessment, performed on proposed insulative building envelope cores. As a result thermal and environmental properties of the proposals are assessed.

Thermal analysis [31]

Thermal analysis of the thermal insulation of building envelopes made of paper materials was carried out using 2D numerical research in ThermCAD software. Material data (heat conductivity coefficient) were selected on the basis of literature data (see Table 4.3) [14]. Numerical studies included a complex model of heat flow through the building partition, taking into account both the solid cellulose material and the air layers inside the semi-finished products.

Table 4.3. Thermal conductivity coefficient of core materials [168].

Name of material	Type of material	Thermal conductivity [W/mK]
Paperboard	-	0.14
Paper honeycomb panel	50 mm thick	0.125
	25 mm thick	0.095
	12.5 mm thick	0.075
Corrugated cardboard	E - flute	0.057
	C - flute	0.053
	BC – flute	0.050
	A – flute	0.047
Cellulose granulate	-	0.039
Wood	-	0.120
Air layer	20 mm	0.180

Firstly, the thickness of building partitions was estimated for homogeneous materials (e.g. made only of BC type corrugated cardboard layered on top of each other). Initial partition thicknesses were obtained as the results of analytical calculations performed in accordance with ISO 6946:2017 standard [71]. During the calculations, the direction of heat flow through the partition was taken into account by selecting appropriate coefficients of thermal resistance of the internal

[31] Research from this section was conducted by Paweł Noszczyk.

and external surfaces – R_{si}=0.13 m^{2}K/W (internal surface) and R_{se}=0.04 m^{2}K/W (external surface). The recommended initial thicknesses were selected so that they were a multiple of the thicknesses of semi-finished products available on the market and to meet the current legal requirements in Poland, which are consistent with European requirements (0.20 W/m^{2}K for the external wall). The U-values should be related to the cores themselves, as a technology for erecting a building partition. Correction of the U coefficient for thermal bridges (such as window connection, corners, ceiling connection, etc.) is not included, because it is possible only when considering a specific building object where the geometry and length of thermal bridges are known.

Knowing the minimum thicknesses of homogeneous envelopes, structural systems of individual designs were proposed. For all cores structures, a repeating non-homogenous section of the partition was selected, which was subjected to the numerical analysis of the stationary heat flow. 2D numerical calculations were made in ThermCAD software for stationary heat flow conditions, assuming the temperature of the internal air as +20°C and the temperature of the external air as -20°C (see Figure 4.2). Such boundary conditions allowed for additional checks on the risk of exceeding the dew point on the inside of the external wall due to the presence of thermal bridges.

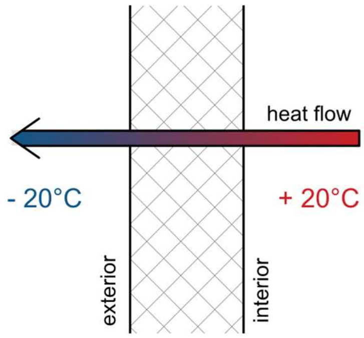


Figure 4.2. Heat flow conditions.

LCA analysis

The LCA process was divided into four stages according to ISO14040 standard, which are: goals and scope definition, life cycle inventory analysis, life cycle impact assessment and interpretation [184]. The Life Cycle Assessment was conducted using OpenLCA software, in accordance with ISO 14040 and ISO 14044 standards [184,185].

<u>Goals and scope</u>

The aim of the study was to analyse the environmental impact of six paper-based building envelope cores, that may be used in small-scale buildings (e.g. single-family housing) in Poland, providing thermal and acoustic comfort. Moreover, the paper-based envelope cores are compared to conventional envelope structures with similar performance characteristics (see Figure 4.3), which are:

- SIP panel envelope, made of 14 cm thick polyurethane foam finished with 15 mm thick OSB board on both sides,
- timber frame wall, made of timber studs with a cross-section of 16x6 cm at a spacing of 60 cm, 16 cm thick mineral wool insulation (between the studs) + an additional 8 cm (from the outside), finished on both sides with 12 mm thick OSB.

The results of the study may prove the environmental benefits of using paper-based building envelopes instead of conventional building materials. Moreover, it should indicate the most environmentally beneficial envelope core designs, providing guidelines for further development.

Considering the design stage and available data, the LCA analysis for each case study was performed including the Product stage and End of Life stage (A1-A3 and C2-C4 according to EN 15804 standard) [186]. Due to the insufficient quantity and quality of data at this stage of the study, the Construction, Use and Demolition phases (A4-B7), as well as the environmental loads associated with the manufacturing prefabrication of the final products, were excluded from the analysis. As shown by Keelenber and Althouse, consciously done simplification may not affect the quality of LCA results [187]. Moreover, the highest rate of building environmental burden is generally linked to the production phase [10,188,189], and according to Hoxcha et al. there is no correlation between building impact during the exploitation phase and building materials used [10]. In the discussed case, due to the similar production technology and performance of the cores, it can be assumed that these phases should not have a significant impact on the results of the analysis.

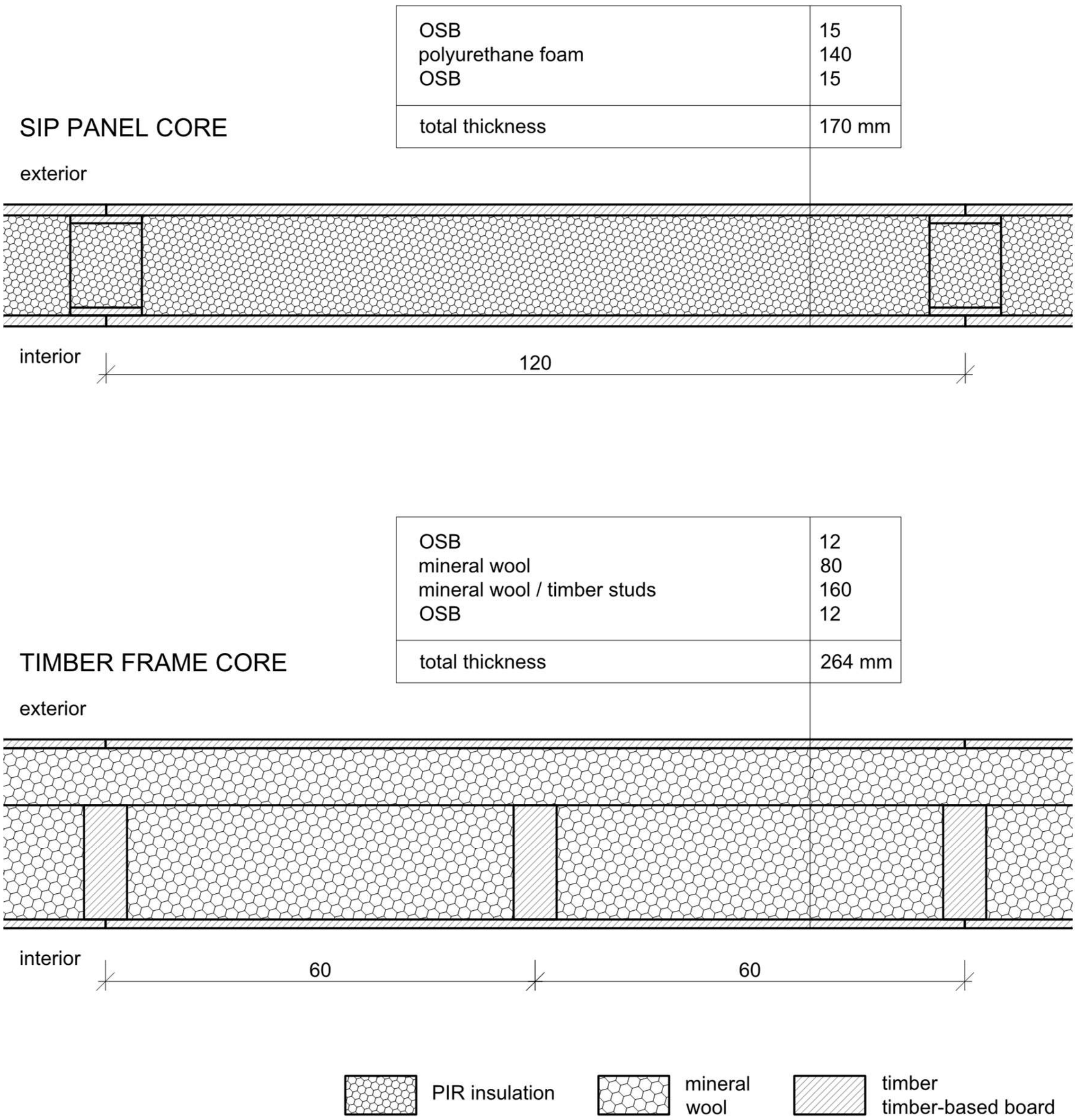


Figure 4.3. Section of envelope cores used for comparison.

Life cycle inventory

The life cycle inventory for the analysis was based on envelopes technical drawings and the Ecoinvent 3.8 database, using data characteristics for Europe. The Ecoinvent, developed since 2000, provides information on a large variety of products and processes with a focus on the European context [190]. Moreover, the database provides extensive information on wood and paper products, that are used in the study [191]. The material inventory of each of the analysed envelopes is presented in Table 4.4.

Table 4.4. Material inventory of the envelopes, presented in kg per average m² of the envelope.

	1A	**1B**	**2A**	**2B**	**3A**	**3B**	**SIP panel**	**Timber frame**
corrugated cardboard	3.894	9.894	3.405	35.927	17.496	14.058	-	-
honeycomb panels	-	-	5.875	1.721	0.326	1.185	-	-
adhesive	0.580	3.067	2.024	13.340	1.600	0.600	-	-
cellulose	7.595	5.058	4.075	-	0.750	1.917	-	-
paperboard	9.000	9.000	9.000	36.000	9.000	9.000	-	-
plywood	-	4.800	4.800	2.000	2.400	-	-	-
timber	4.125	-	0.688	2.063	-	1.375	-	9.600
paper tube/profile	-	-	4.000	12.667	4.083	4.083	-	-
OSB board	-	-	-	-	-	-	19.030	15.600
polyurethane foam	-	-	-	-	-	-	4.480	-
mineral wool	-	-	-	-	-	-	-	47.200

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

- all paper-based products used in partitions are made from 100% recycled fibre, which is in line with the Polish paper manufacturers' product range;
- 90% of the corrugated cardboard, paperboard and honeycomb panels used are recycled at the End of Life phase;
- the remaining waste is disposed of in accordance with standard waste management methods in Poland.

<u>Life cycle impact assessment</u>

The Life Cycle Impact Assessment (LCIA) methods can be divided into two categories, called midpoint and endpoint. Midpoint impacts refer to the intermediate point of the chain, between the emission and the damage caused. They are quantifiable, presented in respective units, and can be linked to specific emissions. Midpoint level methods (also called problem-oriented methods) present product system burdens in several environmental impact areas, e.g. global warming or land use. On the other hand, endpoint methods (also called damage-oriented methods) translate midpoint results into the endpoint impact (damage) caused to the ecosystem or human health [192]. The complementary use of both approaches is recommended, as the midpoint approach can reduce uncertainties, while endpoint one provides easily comparable results [193].

In this study, LCIA was conducted on the basis of inventory modelled in OpenLCA software, using both midpoint and endpoint methods, to provide a wider perspective and more reliable conclusions [194]. The midpoint method chosen was CLM, which analyse the impact in seven categories, in accordance with EN 15804 standard: global warming, ozone layer depletion, photochemical oxidation, acidification, eutrophication, fossil fuel abiotic depletion, and elements abiotic depletion [186]. The endpoint impact was modelled using the ReCiPe calculation method with a single indicator.

4.1.3. Results and Discussion

The performed research showed the thermal and environmental benefits of the proposed envelope designs, however, some important differences between the proposals were identified.

Thermal analysis [32]

For the initial determination of the geometry of the designed cores, the following results were obtained regarding the recommended minimum thicknesses of material-homogenous building envelopes, so as to meet the current legal requirements and use a multiple of semi-finished products available on the market (Table 4.5 and Figure 4.4).

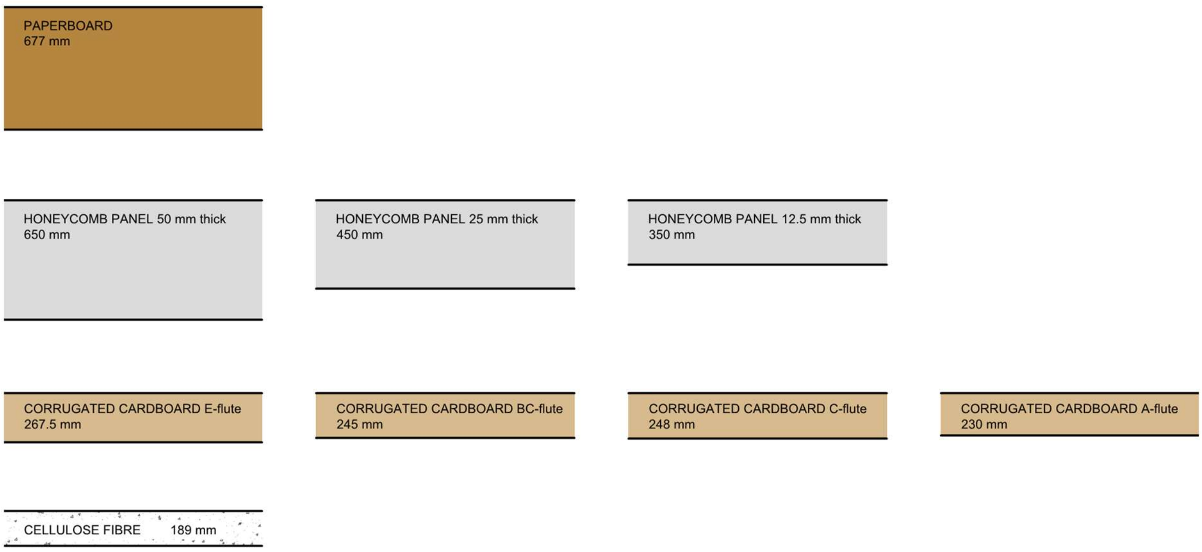


Figure 4.4. Thickness comparison of homogenous paper-based panels (expanded to a multiple of the thickness of a single sheet).

[32] Research from this section was conducted by Paweł Noszczyk.

Table 4.5. Minimum thickness of building partitions that meet Polish legal requirements for thermal insulation of external wall (Umax=0.20 W/m2K).

Material	**Thickness of wall [mm]**
Paperboard	677
Honeycomb panel h=50mm	612
Honeycomb panel h=25mm	435
Honeycomb panel h=12.5mm	350
Corrugated cardboard E-flute	267
Corrugated cardboard BC-flute	240
Corrugated cardboard C-flute	247
Corrugated cardboard A-flute	230
Cellulose fibre	189

The result of 2D numerical calculations was the distribution of the temperature in the cores - isotherms (Figure 4.5) and the value of Q, i.e. the heat flux density (heat flow) flowing through the considered elements under assumed boundary conditions. After iterative optimization of the partition structure in order to obtain the U-value for the external wall below the value of 0.20 W/m^{2}K – detailed results are presented in Table 4.6.

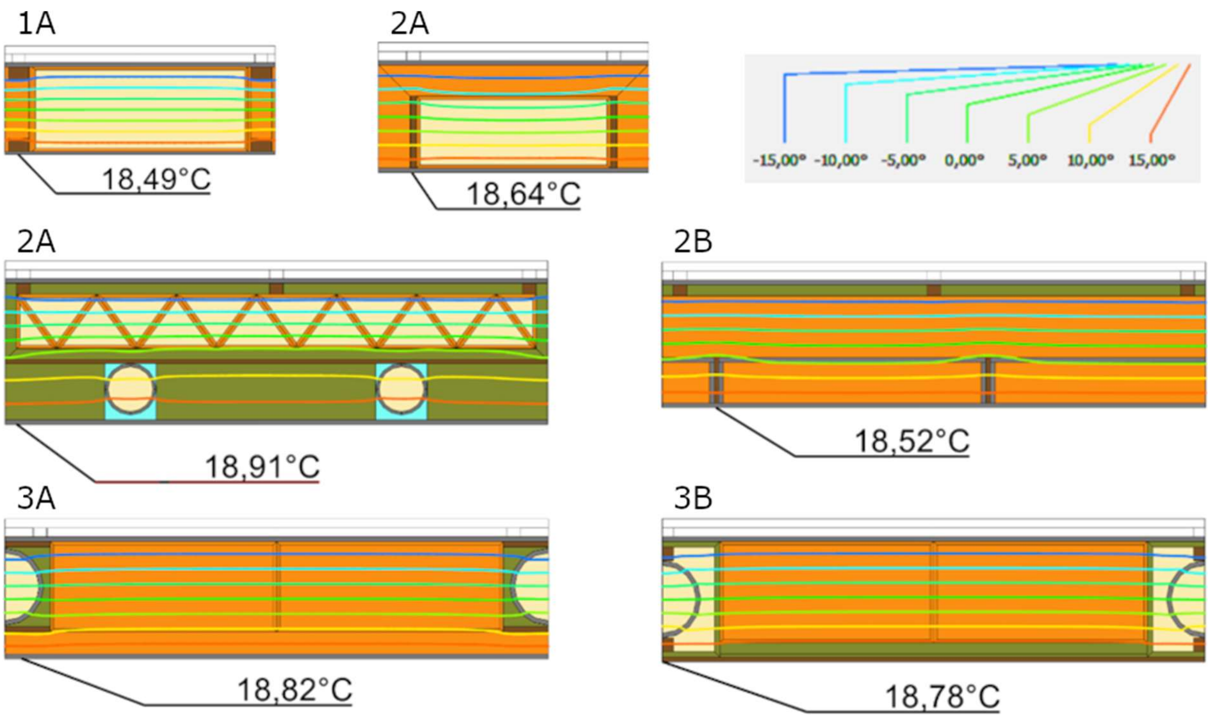


Figure 4.5. Distribution of the temperature field in the walls.

All adopted geometric models of envelopes have a heat transfer coefficient U below the limit value of 0.20 W/m^{2}K. In addition, the results of the numerical analysis showed no problems with the surface condensation of water vapor on the internal surface of the partition (exceeding the dew point). Surface temperatures on the inside for all cases are above 18°C (for the boundary condition -20°C outside and +20°C inside).

Table 4.6. Results of numerical calculations of heat flow through the adopted geometries of external walls

Envelope No. [-]	Length of model l [mm]	Q [W/m]	U-Value [W/m2K]
1A	632	5,031	0,1990
1B	600	4,621	0,1925
2A	1200	9,423	0,1963
2B	1200	9,485	0,1976
3A	1200	9,500	0,1979
3B	1200	9,362	0,1950

LCA analysis

The results obtained from both LCA analyses (see Figures 4.6 and 4.7) reveal significant differences between the discussed case studies. Firstly, core 2B (sandwich structure composed of multiple laminated corrugated cardboard layers) has a significantly larger environmental impact (EI) than any other core analysed. The result can be linked with the envelope weight, as the 2B variant is approximately three times heavier than other paper cores. Moreover, the lowest EI is associated with the lightest of the cores (1A). Also, the adhesive consumption can be linked with the envelope LCA performance, as cores with the lowest adhesive usage present the lowest EI (1A, 3B) and core 2B – the highest one. Furthermore, all of the paper-based cores (except the 2B) presented environmental advantage over the conventional envelopes, in both LCA approaches.

In the endpoint analysis, the highest impact is located in the human health area, especially human toxicity. Other important categories are fossil depletion and natural land transformation. According to midpoint analysis, the fossil fuels consumption for paper-based envelopes ranges from 147 MJ (1A) to 1070 MJ per m^2 (2B) and CO_2 eq. emission – from 1.56 kg (1A) to 8.77 kg per m^2 (2B).

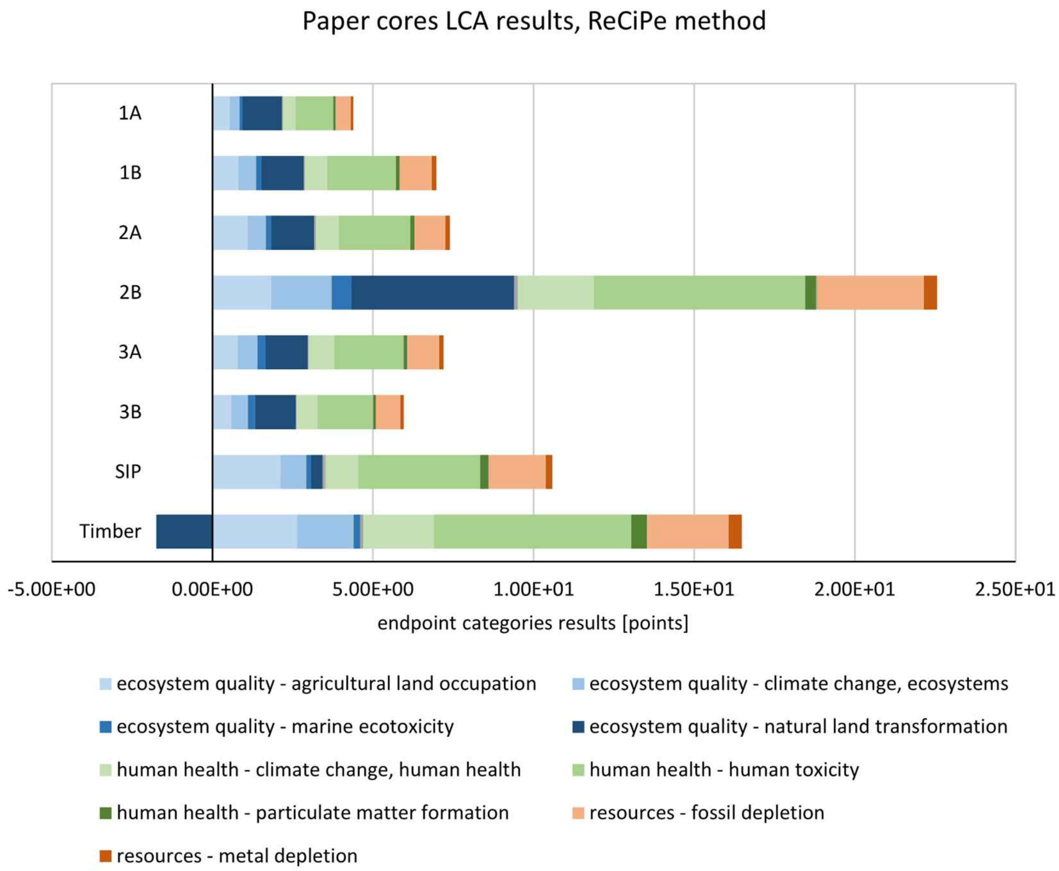


Figure 4.6. LCA results according to the ReCiPe endpoint method, total normalised environmental impact.

The conducted research confirms, that paper cores can be thermally efficient components of a building envelope. The obtained LCA results correspond with the conclusions of Bach [173], showing the environmental superiority of embedded frame structure paper envelopes over sandwich ones. The advantage comes mainly from reductions in weight and adhesive consumption. Furthermore, it can be noticed that the use of insulative boxes filled with cellulose (core 1A) results in lower EI than in the case of corrugated cardboard-filled ones (3A, 3B). Generally, cellulose fibre as thermal insulation is more environmentally friendly than corrugated cardboard, due to its low weight and simple production process. This correlation was also shown by Asdrubali et al. and Secchi et al. [78,90]. However, the cellulose blowing process implies additional technical difficulties, requiring the use of specialised equipment and rigid moulds that prevent paper from tearing due to the high air pressure. Therefore, ease of processing together with the structural properties is an additional advantage of corrugated cardboard insulation.

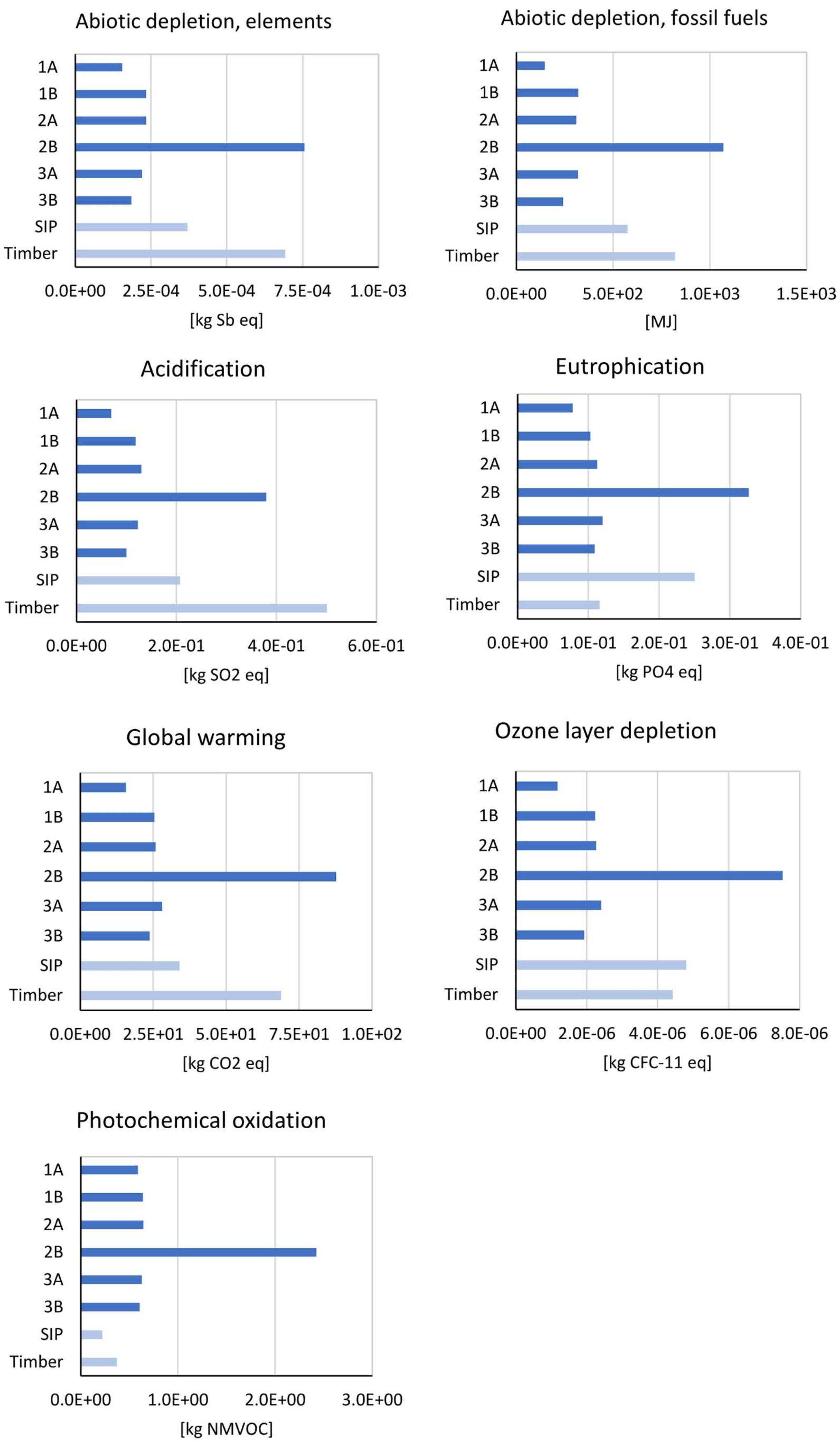


Figure 4.7. LCA results according to CLM midpoint method.

4.1.4. Findings

This subchapter presented the thermal and environmental benefits of building envelopes composed of paper-based materials. All proposed designs showed high thermal insulation properties and met the requirements for U_{max}=0.20 W/m^{2}K. The use of paper-based structural elements led to the reduction of thermal bridges. The analysed building envelope designs based on embedded frame structures showed environmental superiority over conventional timber and SIP envelopes. There was a positive correlation between core weight and its environmental impact, therefore the use of sandwich elements is not recommended, as their heavy weight and excessive adhesive consumption translate into high EI.

Answers to research questions

Q1: How can a structure of paper-based envelops be formed, to ensure structural stability and efficient material consumption?

A1: According to the conducted research, the embedded frame structure type allows for efficient material consumption and, in consequence, low environmental impact. To ensure the structural stability of the component, linear loadbearing elements may be made of paper tubes filled with cellulose (for thermal bridge reduction) or composite stus of corrugated cardboard and timber.

Q2: How to thermally insulate building envelope with paper-based products, without compromising its environmental qualities?

A2: According to obtained results, paper-based building envelopes may be thermally insulated with corrugated cardboard of higher flute types (e.g. BC-flute), thin honeycomb panels (10-25 mm thick) and cellulose fibre. If those elements do not transfer loads, it is highly recommended to avoid or reduce adhesive consumption in the insulation layers. It may be achieved by encasing unglued insulative material in cardboard boxes, working as prefabricated insulative panels and pleaced between structural elements of the envelopes.

4.2. Outer layers [33]

Paper-based building envelope requires outer layers protecting it against water, fire and mechanical damages, which may significantly increase the components' environmental impact, weight and manufacturing costs. This subchapter proposes fourteen original outer layers designs, suitable for use on indoor, outdoor and roof surfaces. All the designs combine various protective materials and complementary coating techniques. The environmental impact of the proposed designs was assessed via Life Cycle Assessment analysis based on Ecoinvent 3.8 database. The proposals' performance was 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.

Research questions

Q1: How can the outdoor surface of paper-based envelope be protected against weather conditions, fire and mechanical damage?

Q2: How can the indoor surface of paper-based envelope be protected against fire and damage resulting from the room's use?

[33] Research from this subchapter is undergoing the review process in Architectural Engineering and Design Management (as at April 2023).

4.2.1. Envelope outer layers design

A series of outer layers for paper-based cores was designed, based on research described in previous chapters and authors' experience from research and works with paper architecture. Proposals cover seven layers for outdoor surfaces application, 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.

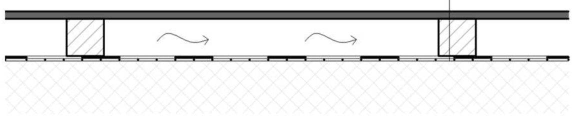
- Each design should form a non-combustible finishing layer, to prevent the spread of fire through the surface and slow down fire penetration into the envelope;
- all the designs suitable for outdoor conditions should feature ventilated air cavities and permeable finish of core surface, to avoid water 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 finishes;
- all the designs shell 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 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. Materials used for roof-appropriate designs are aluminium sheet, 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 4.7 and Figure 4.8.

On the contrary, part of designs for indoor spaces is based on paperboard (that provides stiffness and certain fire protection [39]) 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 4.8 and Figure 4.9.

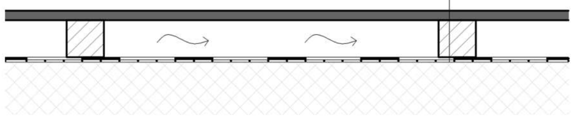
E1

HPL board (fire retardant)	6
ventilation / battens	30
breather membrane	0.5
FR coating - Burnblock	-
total thickness	36.5 mm



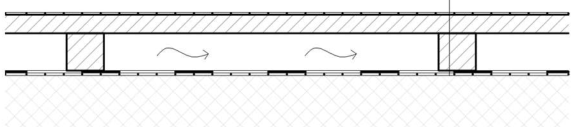
E2

fibre-cement board	8
ventilation / battens	30
breather membrane	0.5
FR coating - Burnblock	-
total thickness	38.5 mm



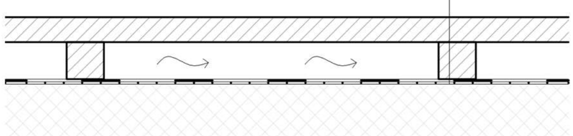
E3

FR wood varnish	-
plywood	15
ventilation / battens	30
breather membrane	0.5
FR coating - borates	-
total thickness	45.5 mm



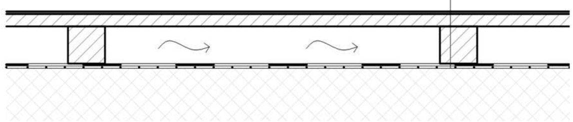
E4

carbonized wood	20
ventilation / battens	30
breather membrane	0.5
FR coating - Burnlock	-
total thickness	50.5 mm



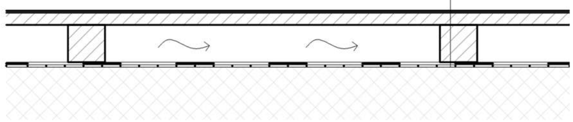
E5

coated aluminum sheet	0.5
FR coating - Burnblock	-
OSB/MDF board	10
ventilation / battens	30
breather membrane	0.5
FR coating - Burnblock	-
total thickness	41 mm



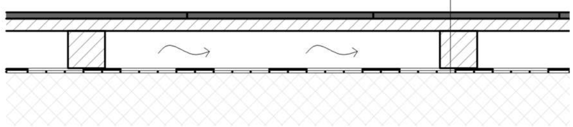
E6

EPDM membrane (fire retardant)	2
OSB/MDF board	10
ventilation / battens	30
breather membrane	0.5
FR coating - borates	-
total thickness	42.5 mm



E7

bitumen shingle (fire retardant)	2
OSB/MFP board	10
ventilation / battens	30
breather membrane	0.5
FR coating - borates	-
total thickness	42.5 mm



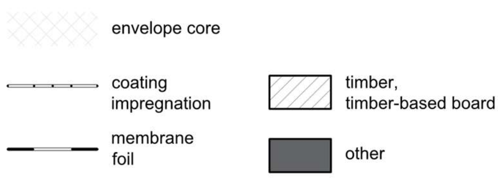


Figure 4.8. Exterior outer layers designs.

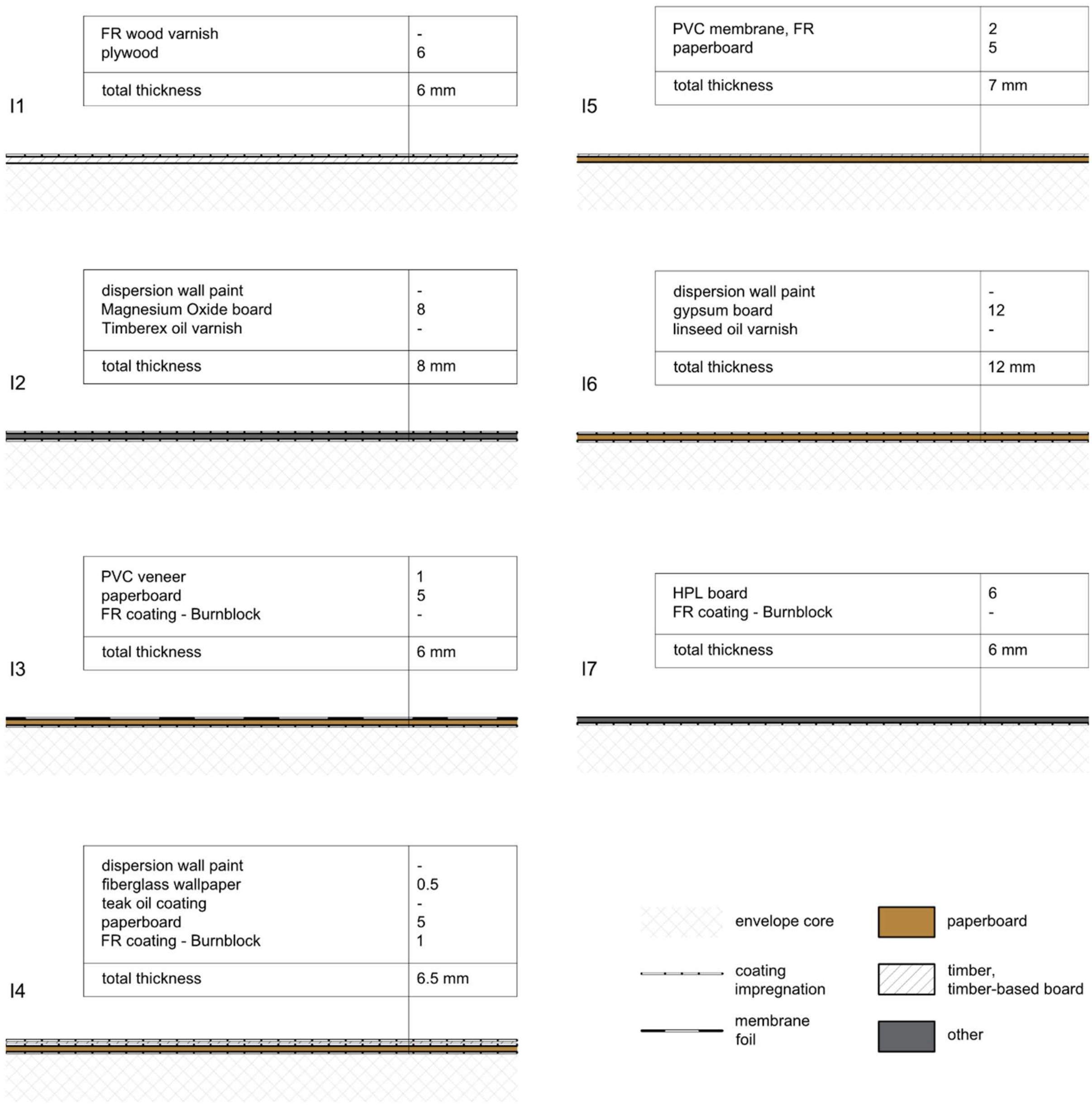


Figure 4.9. Interior outer layers designs.

Table 4.7. Characteristic of outdoor surface outer layers.

No	application	Thickness [mm]	Weight [kg/m²]	Fire resistance	Water resistance	Mechanic. resistance
E1	wall	36.5	2.98	moderate	moderate	high
E2	wall	38.5	13.50	high	moderate	high
E3	wall	45.5	10.95	moderate	moderate	moderate
E4	wall	50.5	4.80	moderate	moderate	moderate
E5	wall and roof	41.0	7.88	high	high	high
E6	wall and roof	42.5	8.83	moderate	high	high
E7	wall and roof	42.5	16.90	moderate	high	high

Table 4.8. Characteristic of indoor surface outer layers.

No	application	Thickness [mm]	Weight [kg/m²]	Fire resistance	Water resistance	Mechanic. resistance
I1	dry rooms	6.0	6.30	moderate	moderate	moderate
I2	dry rooms	8.0	8.30	high	low	moderate
I3	wet rooms	6.0	0.89	low	moderate	low
I4	dry rooms	6.5	1.00	moderate	low	low
I5	wet rooms	7.0	3.00	moderate	moderate	low
I6	dry rooms	12.0	8.36	high	low	moderate
I7	wet rooms	6.0	2.98	moderate	moderate	moderate

4.2.2. 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.

LCA analysis

LCA analysis was performed according to the methodology described in previous subchapter, in section 4.1.4.

<u>Goals and scope</u>

The aim of the analysis was 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 were evaluated separately. The functional unit for all of the analysed case studies was $1m^2$ of the protective layer. 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. The study indicated designs with the lowest environmental burden, that may be recommended for further development and real-life applications in architecture.

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. The material inventory for analysed designs is presented in Tables 4.9 and 4.10.

Life cycle impact assessment

To increase the accuracy of the results, two different impact assessment methods were implemented – the midpoint CLM and the endpoint ReCiPe method. The ReCiPe results are also presented as a single indicator, allowing direct comparisons between evaluated scenarios [192,193,195].

Performance assessment

The performance characteristic was assessed via Performance Score (PS), consisting of summarised results in four categories: fire resistance, water resistance, mechanical resistance, price and availability. Each design was given a rating in each category from 0 (lowest) to 2 (highest), based on design components characteristics provided by manufacturers and literature review. Properties of coatings and impregnantes are provided in Table 4.11, properties of finishing materials – in Table 4.12. Scores in each category are summed to give a total PS from 0 to 8.

Table 4.9. 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 4.10. 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	-

Table 4.11. Coatings and impregnates for paperboard.

Product and manufacturer name	Base material	Water resistance	Fire resistance	Price
Timberex hard wax oil	natural oils and waxes	high	moderate	high
Colorit wood wax	synthetic and natural waxes	moderate	low	low
Dragon linseed oil varnish	linseed oil	high	low	low
Burnblock	natural occurred compounds	-	high	moderate
Borates fire retardant	sodium borate-boric acid 1:1 mixture	-	high	low

Table 4.12. Finishing materials proposed for use on paper-based building envelopes.

Material	Thickness [mm]	Weight [kg/m2]	Fire resistance	Water resistance	Mechanical resistance	Price [1]
aluminium sheet	0.60	1.50	high	high	low	low
plywood	18.00	10.80	moderate	moderate	high	high
fibre-cement board	10.00	13.20	high	high	high	low
HPL board	5.20	2.68	high	high	high	high
EPDM membrane, FR	1.80	2.45	high	high	high	low
PVC membrane	1.80	2.50	low	high	high	low
fibreglass wallpaper	0.50	0.05	high	high	high	low
vinyl veneer	0.50	0.75	moderate	high	high	low
carbonised timber	20.00	11.00	moderate	moderate	high	high
magnesium oxide (MgO) board	8.00	8.00	high	high	high	high
gypsum board	12.00	8.06	moderate	low	moderate	low
bitumen shingle, FR	2.00	10.00	moderate	high	high	low

[1] low price – less than 25€ per m^2, moderate – 25-50€, high – over 50€. Estimated based on market prices in Poland in 2022.

4.2.3. Result 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 indication of the most beneficial design variants from each layer group.

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 impact 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 was 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 Figure 4.10). As presented by CLM analysis (see Figure 4.11), 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).

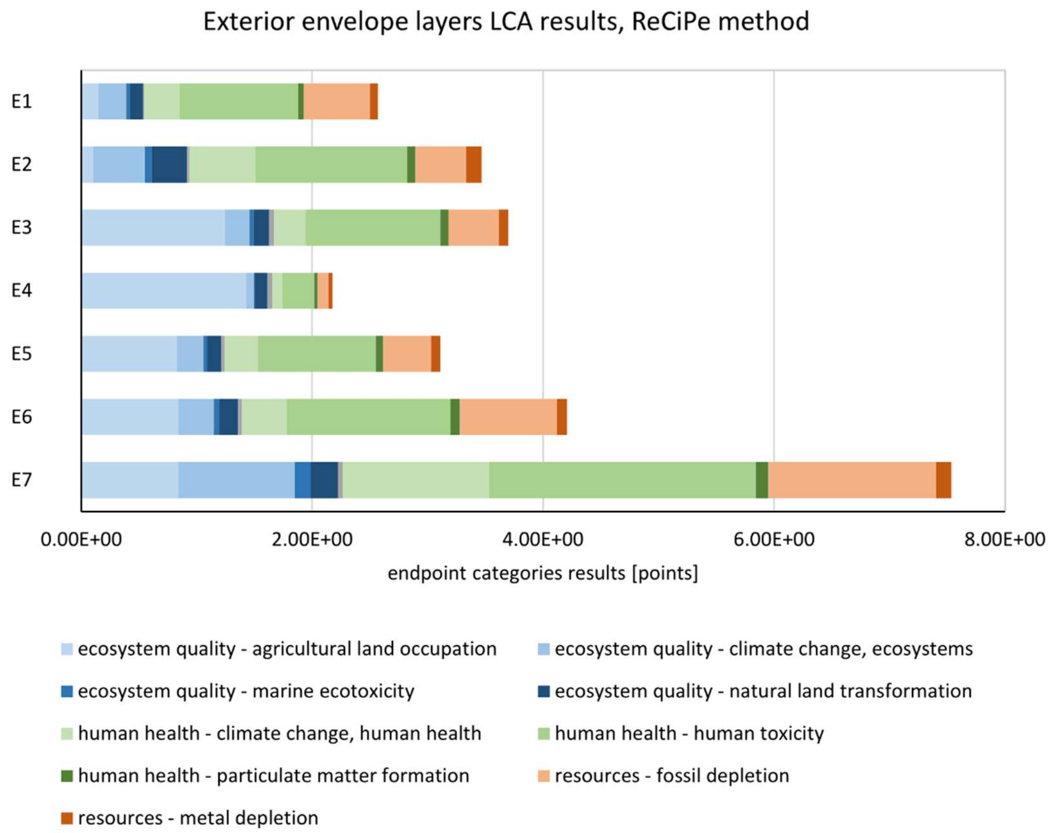


Figure 4.10. Result of ReCiPe method endpoint LCA analysis for exterior layers E1-E7.

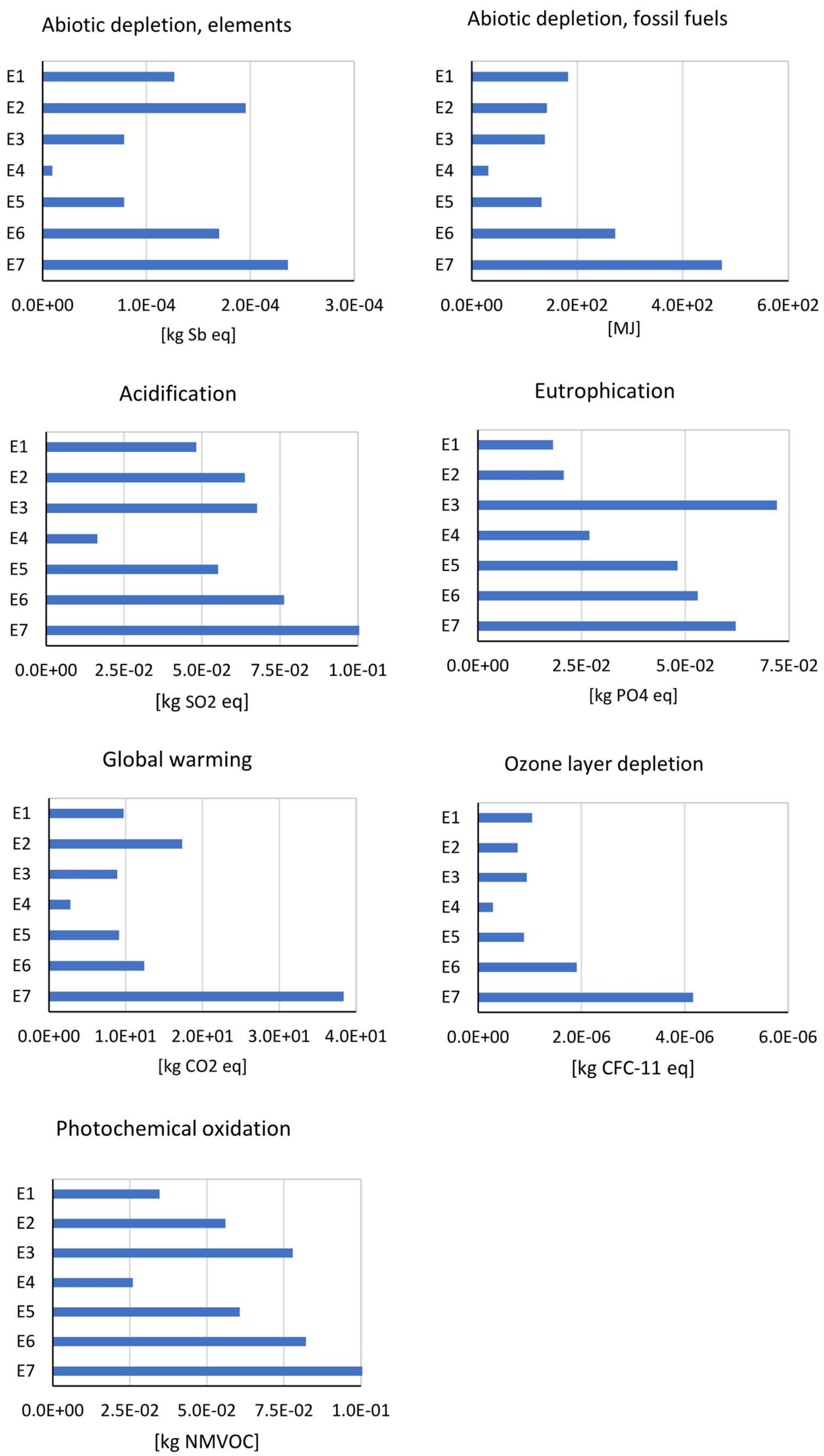


Figure 4.11. Result of CLM method midpoint LCA analysis for exterior layers E1-E7.

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 Figure 4.12). In the categories of midpoint analysis, a bigger variety was observed (see Figure 4.13). 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).

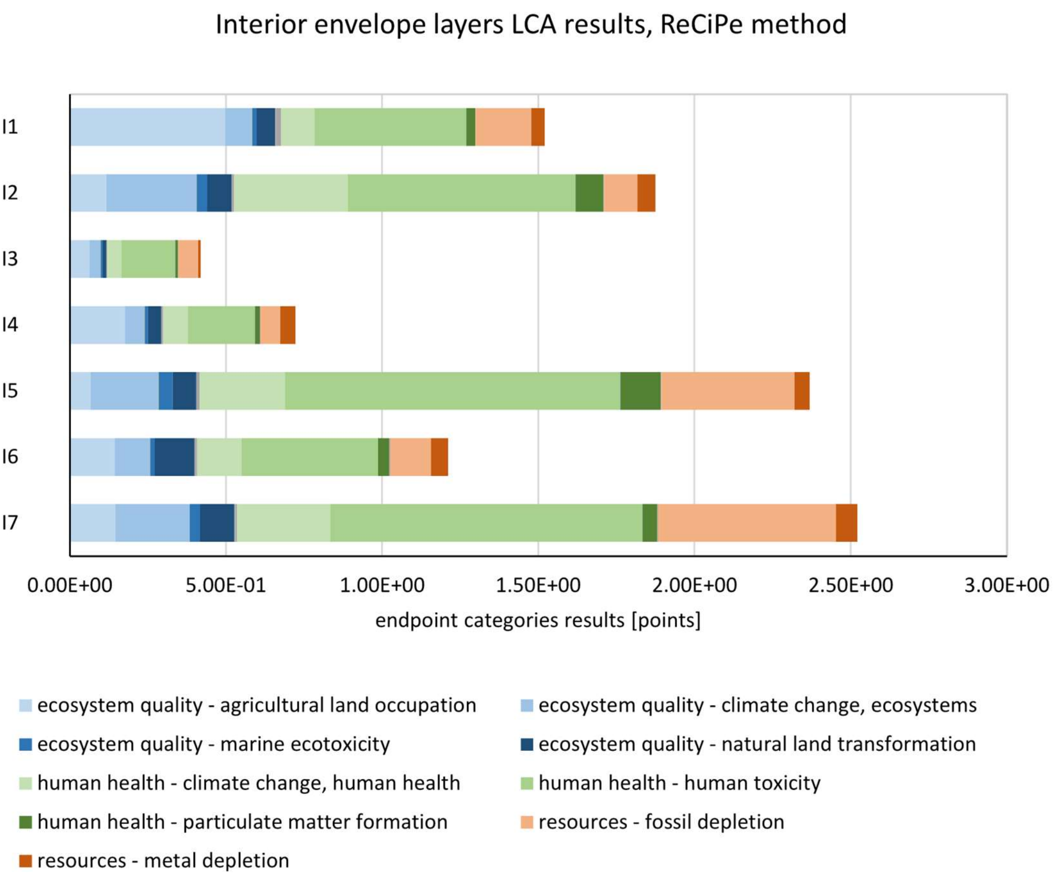


Figure 4.12. Result of ReCiPe method endpoint LCA analysis for interior layers I1-I7.

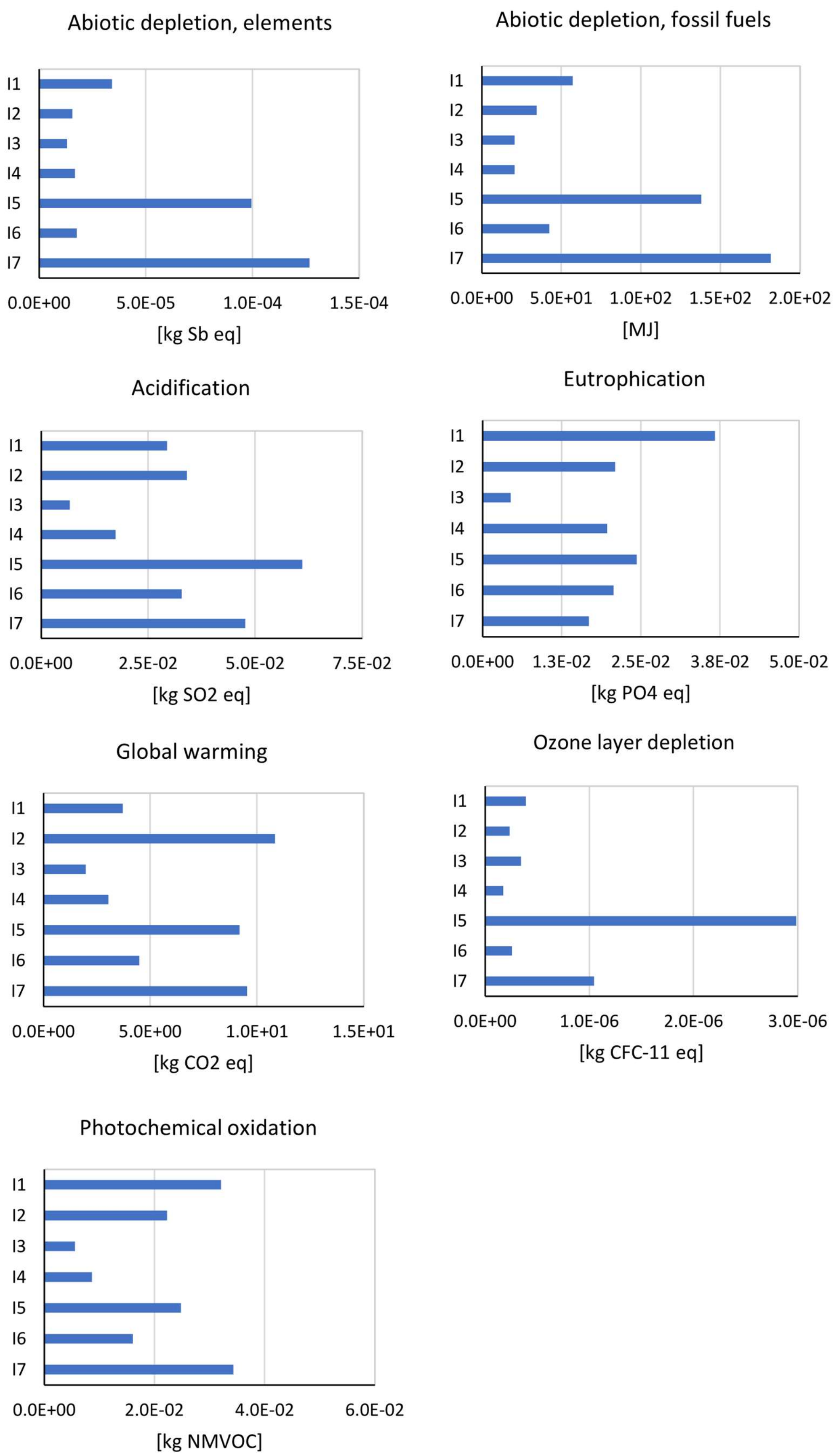


Figure 4.13. Result of CLM method midpoint LCA analysis for interior layers I1-I7.

Outer layers evaluation

Based on materials characteristics the designs' Performance Score 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 4.13). Secondly, the PS was juxtaposed with single-indicator LCA results. The designs with high PS and low EI (indicated by the yellowish quarter in the plots in Figure 4.14) can be recommended as the most optimal solutions.

Table 4.131. 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 – interior dry room, IW – interior wet room

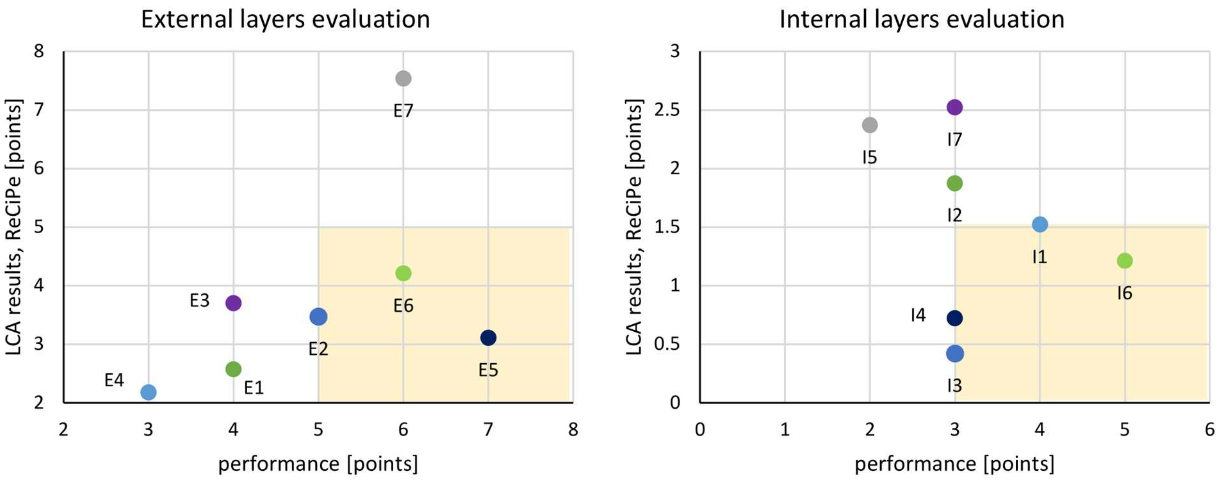


Figure 4.14. Outer layers evaluation metric.

Considering outdoor-appropriate layers, designs E5 (aluminium sheet) and E2 (fibre-cement board) can be recommended. The E6 design also performed highly, however, the use of EPDM 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 magnesium oxide board, may noticeably increase the acoustic properties of lightweight partition walls, while lightweight proposals (e.g. fibreglass or PCV veneer) should be considered when low weight is a key factor, for example in temporary structures.

4.2.4. Findings

In this subchapter fourteen design proposals of protective outer layers for paper-based envelopes were presented and analysed in terms of their performance, characteristics and environmental impact. All the designs combine various materials and complementary coating techniques, in order to achieve optimal performance. Depending on the materials, various mechanical, fire and water resistances 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 pro-ecological properties of paper-based envelopes. Materials such as fibre-cement boards, HPL boards and metal cladding, combined with ventilated air cavities, can be recommended for use as the sustainable outer layers in outdoor surfaces, while gypsum plasterboard or paperboard laminated with PVC or fibreglass veneer – for the indoor parts.

Answers to research questions

Q1: How can the outdoor surface of paper-based envelope be protected against weather conditions, fire and mechanical damage?

A1: According to the research results, the optimal protection of the external core surface may be achieved by a combination of durable cladding materials, lamination, fire retardant impregnation and ventilation. It is important to ensure high vapour permeability of the materials between the core and ventilated cavity. The choice of natural cladding materials, such as mineral, metal or timber-based board leads to a lower environmental burden of the envelope.

Q2: How can the indoor surface of paper-based envelope be protected against fire and damage resulting from the room's use?

A2: As shown by the analysis results, indoor surfaces of envelopes may be protected by laminated or painted paperboard, as well as by non-paper cladding made of mineral or timber-based boards. However, the latter generates a higher environmental impact.

Chapter 5

Macroscale – building envelope [34]

Results of research and layers proposals from Chapter 4 served as input for the design of two full-performance paper-based building envelopes. The cores chosen for final designs were cores 1A and 3A, the outer layers – E1, E2, I3 and I4. The initial designs were modified and optimised based on the prototyping process, consultations with acoustic and mechanics experts and material availability. As a result, two paper-based cores were proposed – Cardboard Stud Envelope (CSE), consisting of 1A, E1, I3 and Tube Frame Envelope (TFE), consisting of 3A, E2 and I4. In this Chapter, the environmental and functional performance of CSE and TFE was compared with paper-based building envelopes known from literature and envelopes made of conventional building materials. The environmental analysis was conducted via Life Cycle Assessment, using the midpoint CML method and endpoint ReCiPe method with a single indicator. LCA was based on Ecoinvent 3.8 database and supplemented with sensitivity analysis. LCA results were supplemented with performance assessment.

Research questions

Q1: Can the proposed CSE and TFE provide an environmentally friendly alternative to envelopes made of conventional building materials?

Q2: Which factors have the biggest influence on the environmental impact of paper-based envelopes?

[34] Research from this chapter is undergoing the review process in Building and Environment - completed revision after the first round of reviews (May 2023).

5.1. Envelopes designs

The analysis was conducted on eight envelopes with comparable functional properties – two original paper-based designs (outcome of the thesis), three literature-based paper-based designs (sandwich, row and embedded structure), and three standard designs made of conventional building materials. Case studies were selected from literature and market research, as representative examples of lightweight envelopes, according to the following criteria.

- Each envelope consists of a modular structure, insulative core and protective outer layers, at least on the outdoor surface;
- the envelopes offer high thermal insulation, with thermal transmittance U not higher than 0.25 W/m^{2}K (preferably 0.20 W/m^{2}K) and include ventilated façade system;
- selected envelopes contain load-bearing elements allowing for construction of a small building without the need for an additional supporting structure;
- prefabricated elements can be assembled manually, without the use of heavy equipment.

The original proposals of the Cardboard Stud Envelope (CSE) and Tube Frame Envelope (TFE) were designed in the embedded frame approach, based on literature, experimental and prototyping study described in this thesis. The following criteria were obeyed in the design process.

- Paper, cardboard and cellulose fibre as the main building materials, both by volume and weight;
- reduced environmental impact, without compromising the performance;
- U-value of the envelope not higher than 0.20 W/m2K, according to regulations of Polish building code;
- ventilated façade;
- weight of a single component not higher than 50 kg, to enable handling by two persons;
- reduced adhesive connections;
- separability of recyclable materials at the end-of-life phase;
- high fire, water and mechanical damage resistance on external surfaces;
- moderate fire, water and mechanical damage resistance on internal surfaces.

Both envelopes consist of linear structural elements – studs made of corrugated cardboard and timber scantling (CSE) or frame made of cellulose-filled paper tubes with honeycomb panels enclosure (TFE). Structural elements (marked as A in Figure 5.1) are connected by impregnated paperboard panels (B) with breather membrane and cladding creating air cavity. During assembly, boxes (C) filled with thermal insulation (cellulose fibre or unglued corrugated cardboard) are inserted between structural elements, and finishing panels (D, E) are mounted on both sides of the envelope. The elements are connected mechanically with screws and bolts. Structural elements and internal finishing layers are laminated using PVA adhesive, and the paperboard in the outer surface of the core is laminated using dextrin glue with high vapour permeability. The combination of two adhesives with different permeabilities improves paper core ventilation, reducing the risk of condensation and material damage [173]. Fire retardant HPL (high-pressure laminate) and fibre-cement boards were chosen as external claddings, while internal surfaces are protected by PVC veneer or painted fibreglass wallpaper mat on FR paperboard. Detailed sections of CSE and TFE are presented in Figure 5.2.

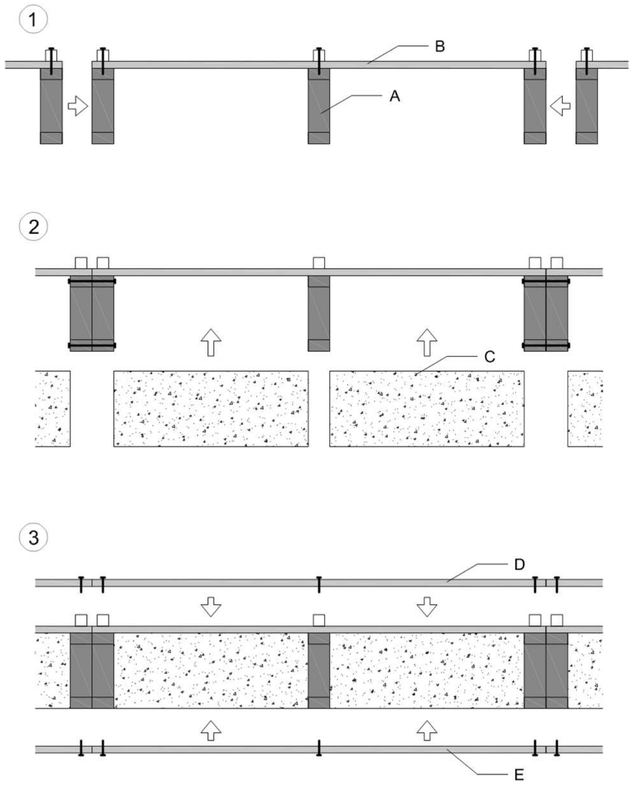


Figure 5.1. Assembly scheme of CSE.

The selected literature-based paper-based envelopes are Integrated Skeleton Façade (ISF) as an example of embedded frame structure [173], Full Performance Paper House Envelope (FPPHE) as sandwich one [53,171] and Archicart Envelope (ACE) as a row design type [172]. The paper-based envelopes were describes in the State of the Ars (section 2.2.1) and their details are presented in Figure 5.3.

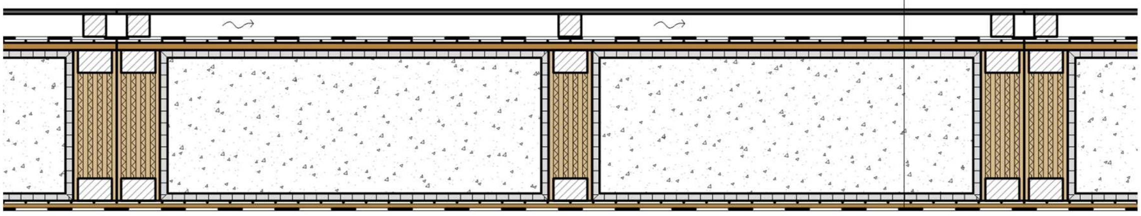
Conventional envelopes chosen for this comparison are based on structural insulated panels (SIP), timber studs and steel profiles. The SIP envelope consists of OSB-EPS (Oriented Stand Board and

Expanded Polystyrene) panels with ventilated cladding on both sides – timber cladding on the outside and gypsum plasterboard on the inside [196]. The selected timber envelope is composed of timber studs and mineral wool insulation, with timber cladding (outside) and gypsum plasterboard (inside) [197]. Steel envelope structure is made of C-shaped steel profiles, insulated with mineral wool and PIR foam boards, with steel cladding on plywood sheathing (outside) and gypsum plasterboard finish (inside) [198]. Sections of the envelopes are presented in Figure 5.4.

The summarised characteristic of compared envelopes is presented in Table 5.1. The thickness of the case studies range from 18.7 cm (Steel E) to 30.0 cm (ISF), and weight per square meter from 19.39 kg (ACE) to 83.25 kg (FPPHE). The efficiency of thermal insulation was assessed via ratios of thermal resistance to envelope thickness (R:d) and thermal resistance to weight per square metre (R:m) [168]. The heat of combustion per square metre of the envelope, which affect the fire load of the building, was calculated in accordance with the materials' calorific values provided in EN 1991-1- 2:2002 standard [174], ranging from 254.08 MJ (Steel E) to 1373.14 MJ (FPPHE).

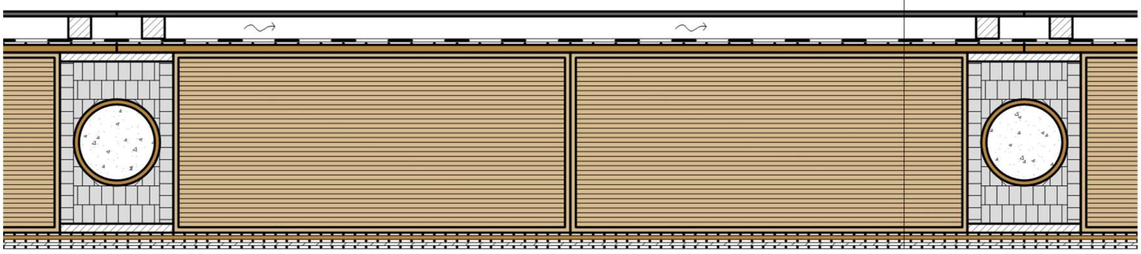
HPL board, FR	6
ventilation / battens	30
breather membrane	0.5
FR coating - Burnblock	-
paperboard, dextrine glued	9
insulation boxes / columns	200
FR coating - Burnblock	-
paperboard, PVA glued	6
PVC veneer	0.5
total thickness	252 mm

1. CARDBOARD STUD ENVELOPE



fibre-cement board	6
ventilation / battens	30
breather membrane	0.5
FR coating - borates	-
paperboard	9
insulation boxes / columns	196
FR coating - borates	-
paperboard	6
fiberglass wallpaper	0.5
dispersion wall paint	-
total thickness	248 mm

2. TUBE FRAME ENVELOPE



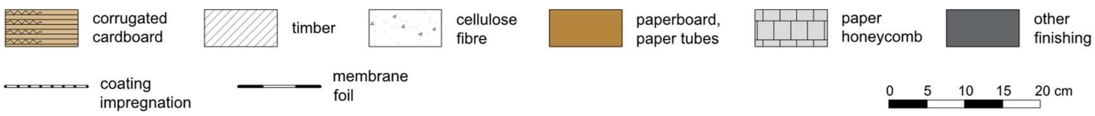
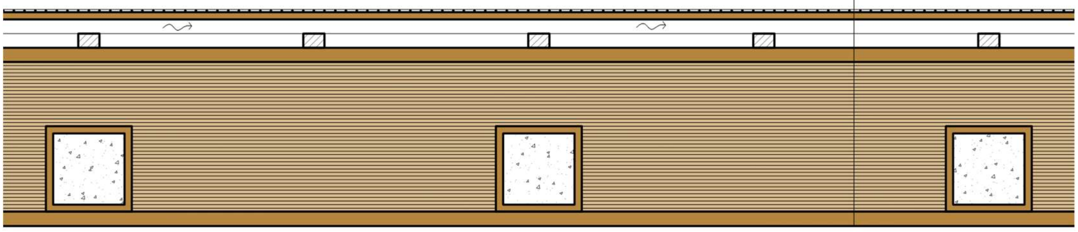


Figure 5.2. Envelopes under study - original paper-based designs.

acrylic paint	-
paperboard, high-density	10
ventilation / battens	40
paperboard, water-resistance	20
corrugated cardboard, A flute	90
corrugated cardboard, A flute / columns	120
paperboard, high-density	20
total thickness	300 mm

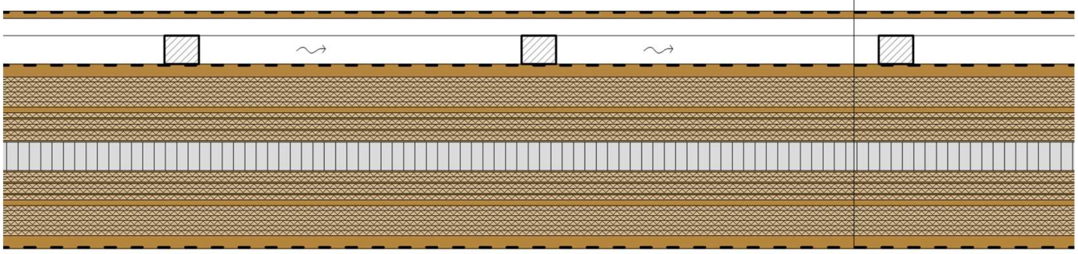
3. INTEGRATED SKELETON FACADE



TetraPack-coated paperboard cladding	30
ventilation / battens	65
paper panel consisting of:	
polyethylene film	-
paperboard *	15
corrugated cardboard BC-flute	42
paperboard *	8
corrugated cardboard BC-flute	7
paperboard (high density)	2
corrugated cardboard BC-flute	14
paperboard (high density)	2
corrugated cardboard BC-flute	14
paperboard (high density)	2
paper honeycomb	40
paper panel, as above	106
total thickness	347 mm

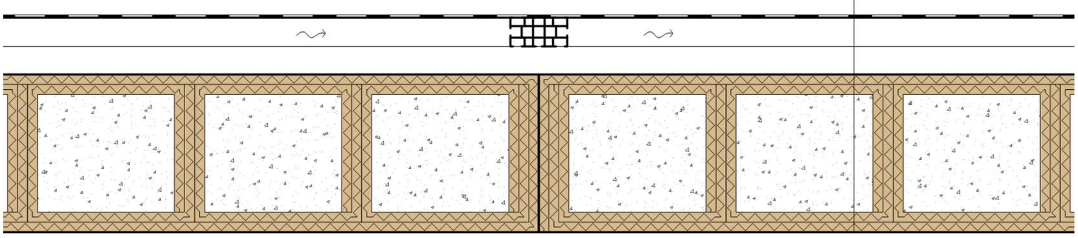
* various types: fire retrdant, high density, self-adhesive

4. FULL PERFORMANCE PAPER HOUSE ENVELOPE



PCV coated textile	0.5
ventilatiom / aluminium profiles	80
Archicart panel (corrug. card. + cellulose)	220
total thickness	300.5 mm

5. ARCHICART ENVELOPE



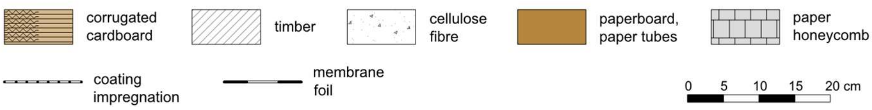
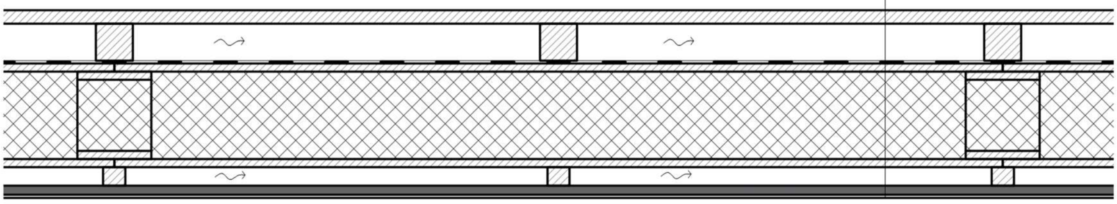


Figure 5.3. Enveloped under study - paper-based envelopes.

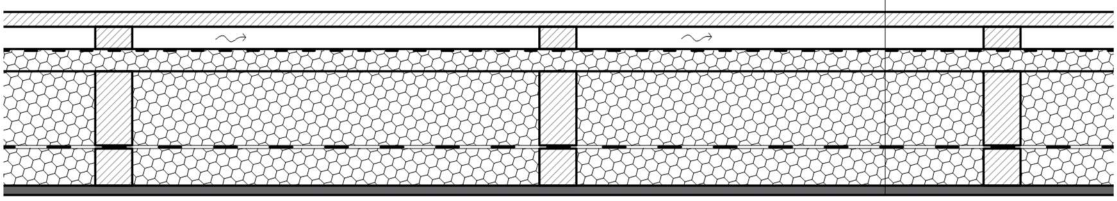
timber cladding	18
ventilation / battens	50
breather membrane	0.5
EPS-OSB SIP panel	140
ventilation / battens	25
gypsum plasterboard	12.5
skim	3
total thickness	237 mm

6. SIP PANEL ENVELOPE



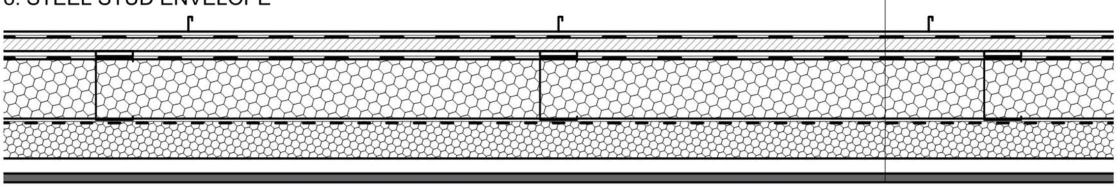
timber cladding	20
ventilation / battens	30
mineral wool with wind insulation	30
mineral wool / wooden beams	100
breather membrane	0.5
mineral wool / battens	50
gypsum plasterboard	12.5
total thickness	243 mm

7. TIMBER STUD ENVELOPE



standing seam steel cladding	0.5
breather membrane	0.5
plywood	18
ventilation / XPS insulative strips	5
breather membrane	0.5
mineral wool / metal profiles	80
PIR board, reflective finish	50
unventilated cavity / metal profiles	20
gypsum plasterboard	12.5
total thickness	187 mm

8. STEEL STUD ENVELOPE



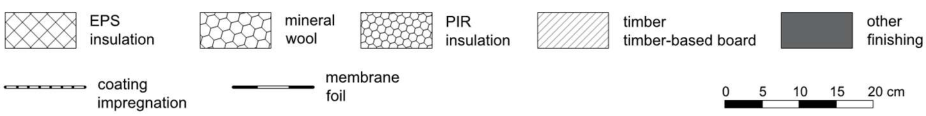


Figure 5.4. Envelopes under study - non-paper envelopes.

Table 5.1. Characteristics of envelopes under study.

		CSE	TFE	ISF	FPPHE	ACE	SIP	Timber	Steel
Thickness [cm]		25.2	24.8	30.0	34.7	30.5	23.7	24.3	18.7
Weight [kg/m2]		38.55	47.26	58.85	83.25	19.39	43.90	46.28	35.25
Heat of combustion [MJ/m2]		634.19	582.16	938.32	1373.14	283.86	583.10	442.17	254.08
R [m2K/W]		5.03	5.05	4.76	3.97	4.56	5.00	5.26	5.00
U [W/m2K]		0.20	0.20	0.21	0.25	0.22	0.20	0.19	0.20
R:d ratio		0.20	0.20	0.16	0.11	0.15	0.21	0.22	0.27
R:m ratio		0.13	0.11	0.08	0.05	0.24	0.11	0.11	0.14
Paper share, by weight		73%	69%	95%	80%	83%	-	-	-
Paper share, by volume		93%	91%	99%	96%	98%	-	-	-
External surface	resistance to water	high	high	low	medium	high	medium	medium	high
	resistance to fire	high	high	medium	low	medium	low	low	medium
	mechanic. resistance	high	high	low	medium	medium	medium	medium	high
Internal surface	resistance wo water	medium	medium	low	medium	low	medium	medium	medium
	resistance to fire	medium	medium	medium	low	low	high	high	high
	mechanic. resistance	medium	medium	medium	medium	low	high	high	high
price and material availability		medium	good	medium	poor	good	medium	good	good

5.2. Methods

The research methodology combines environmental analysis, using Life Cycle Assessment (LCA), and performance analysis, using the numerical indicator of Performance Score (PS).

Life Cycle Assessment

The LCA analysis was performed following the general methodology described in Chapter 4, section 4.1.2, with the additional uncertainty and sensitivity analysis.

Table 5.2. Material inventory for LCA, in kg per 1 m² of the envelope.

	CSE	TFE	ISF	FPPHE	ACE	SIP E	Timber	Steel
corrugated cardboard	1.186	18.995	7.189	12.606	9.943	-	-	-
honeycomb panel	0.844	0.729	-	1.240	-	-	-	-
paperboard	10.500	10.500	41.000	52.870	-	-	-	-
paper tube / shape	-	2.000	6.984	-	-	-	-	-
cellulose fibre	15.750	-	0.794	-	6.188	-	-	-
timber	4.950	0.825	1.048	3.850	-	12.879	24.250	-
plywood	-	1.800	-	-	-	-	-	10.800
OSB	-	-	-	-	-	14.300	-	-
PVA adhesive	0.614	0.406	2.400	-	0.182	-	-	-
dextrin adhesive	0.400	0.400	-	-	-	-	-	-
SBR adhesive	-	-	-	16.250	-	-	-	-
silicate adhesive	-	-	0.486	-	-	-	-	-
borates FR (dry)	-	0.300	-	-	-	-	-	-
Burnblock FR (dry)	0.300	-	-	-	-	-	-	-
breather membrane	0.135	0.135	-	0.405	-	0.135	0.135	0.338
polyvinyl chloride	0.240	-	-	-	0.270	-	-	-
polyethene	-	-	-	-	-	-	-	-
polyester	-	-	-	-	0.300	-	-	-
aluminium	-	-	-	-	2.500	-	-	-
steel	0.114	0.060	0.090	0.090	0.100	0.084	0.095	8.366
HPL board	4.020	-	-	-	-	-	-	-
fibre-cement board	-	10.800	-	-	-	-	-	-
acrylic paint	-	0.150	0.150	-	-	-	-	-
glass fibre	-	0.110	-	-	-	-	-	-
EPS	-	-	-	-	-	2.100	-	-
mineral wool	-	-	-	-	-	-	13.400	5.600
PIR board	-	-	-	-	-	-	-	1.750
gypsum plaster	-	-	-	-	-	6.000	-	-
gypsum plasterboard	-	-	-	-	-	8.400	8.400	8.400

Goals and scope

The aim of the conducted LCA was to assess the environmental benefits of replacing lightweight building envelopes produced from conventional materials with envelopes made mostly from paper, including two original proposals with the embedded structural system. The results were used to indicate the most environmentally beneficial options from all the analysed case studies. Moreover, it assessed the contribution of particular layers and material groups to cumulative envelope impact, allowing for "hot points" identification and further design optimization.

The analysed envelopes are suitable for application in small-scale, single-storey buildings (e.g. single-family houses) in a temperate climate, and provide comparable functional properties, including thermal and acoustic comfort. The adopted functional unit was one square metre of the envelope. The LCA analysis for each case study was performed including the Product Stage and End of Life Stage (A1-A3 and C2-C4 according to EN 15804 standard) [186].

Life cycle inventory

The life cycle inventory for the analysis was developed based on designs presented in section 5.1.1, using background data from Ecoinvent 3.8 database. The material inventory for researched envelopes is presented in Table 5.2.

Life cycle impact assessment

The study was conducted using both problem-oriented (midpoint) and damage-oriented (endpoint) assessment methods [195,199]. The analysis was conducted based on the life cycle inventory, in the OpenLCA software, in accordance with ISO 14040 and ISO 1444 standards [184,185]. The selected endpoint method was ReCiPe, with the Egalitarian approach, thus the environmental burdens are counted regardless of the time between the emission and damage caused (a time horizon of 1 000 years is assumed) [200]. The midpoint method used is CML [201], relevant to EN 155804 standard [186].

Study limitations, uncertainties and sensitivity

Each Life Cycle Assessment is subject to the risk of inaccuracy, due to inadequate data quality, data variability and uncertainties in the assumptions made. Error elimination strategies are particularly relevant for analyses at the design stage, which require more use of generic data. Despite high uncertainties, LCA at the early design stages can lead to the largest EI savings in the final product [202]. Furthermore, according to Hoxha et al. even taking into account high uncertainties, significant differences between analysed scenarios should be visible in LCA results if their impact differs by approximately 20% or more [10].

There are two main sources of uncertainties in the analysis – assumptions made regarding envelopes' performance and materials used, and the impact of the chosen assessment method. For the analysis, it was assumed that all analysed envelopes had comparable performance characteristics, including the expected life span. However, for the purposes of transparency of results, it should be noted that some of the case studies may be less durable in real life due to more sensitive outer layers. The problem was addressed with separate LCA analyses for envelopes' cores. Another aspect outside the scope of the research are benefits and loads beyond the system boundary, in particular the carbon storage ability of cellulose-based products. Inclusion of these loads in the future analysis may led to lower results of greenhouse gases emission [203].

Furthermore, an analysis dividing the contribution of various material groups (paper, adhesives with fire retardants and other materials) to the envelopes' cumulative impact was conducted. It was assumed in the LCI, that 90% of paper-based products are recycled in the end-of-life phase, and all the paper used is produced from recycled fibre. Nevertheless, the scenario without any paper recycling strategies was also analysed and compared.

Bueno et al. and Ferrández-García et al. suggested the use of several calculation methods as the best practice to obtain reliable LCIA results [194,204], which is also recommended as a part of sensitivity analyses by ISO 14044 standard [185]. Three different endpoint weighting methods were applied to assess their impact on the results. Apart from ReCiPe (egalitarian), which results were considered most relevant due to the method up-to-date status, the IMPACT 2002+ and Eco-indicator 99 in the hierarchical (i.e. 100 years horizon) approach were used and compared.

Performance assessment

Apart from LCA, that provides environmental impact information, other indicators should be used for best-informed design decisions, following the multi-objective approach [205]. In the conducted research, the envelopes' performance was assessed via Performance Score (PS), based on the characteristics from Table 5.1, as a sum of numerical assessment in several categories. Each envelope received a score from 0 (lowest performance) to 2 (highest performance) in the categories of U-value, R:d and R:m ratios, as well as 0 to 4 points in the categories of price, water, fire and mechanical resistance. The cumulative PS was later compared with the total LCA score (according to ReCiPe method), to indicate envelopes with the most beneficial performance and environmental characteristics. Analogical analysis was done for insulative cores, where the LCA score was compared with the cores' U-value.

5.3. Results and Discussion

A series of midpoint and endpoint Life Cycle Assessment analyses were performed, revealing significant differences between the analysed case studies. Although the general advantage of paper-based envelopes was proven, their shortcomings were also indicated. Comparison of LCA, PS and U-value results led to final recommendations.

Life Cycle Assessment

To obtain the overview of the analysed problem, the study began with ReCiPe single-indicator analysis, distinguishing cores and outer layers (see Figure 5.5). The cumulative score of the envelopes varies from 7.92 (Timber E) to 37.86 (SIP E), with results for paper-based ones from 12.03 (CTE) to 32.88 (FPPHE). There is an unquestionable superiority visible of the embedded frame and row designs over the sandwich alternative. The only envelope with lower environmental impact than paper-based ones is the Timber envelope, which is consistent with the findings of Bach's study [173]. The ACE and Timber cores are linked with the lowest cumulative impacts, while cores of FPPHE and SIP triple the impact of other scenarios. On the contrary, the lowest burden is associated with outer layers of FPPHE, SIP E and Timber E, and the highest – with Steel E.

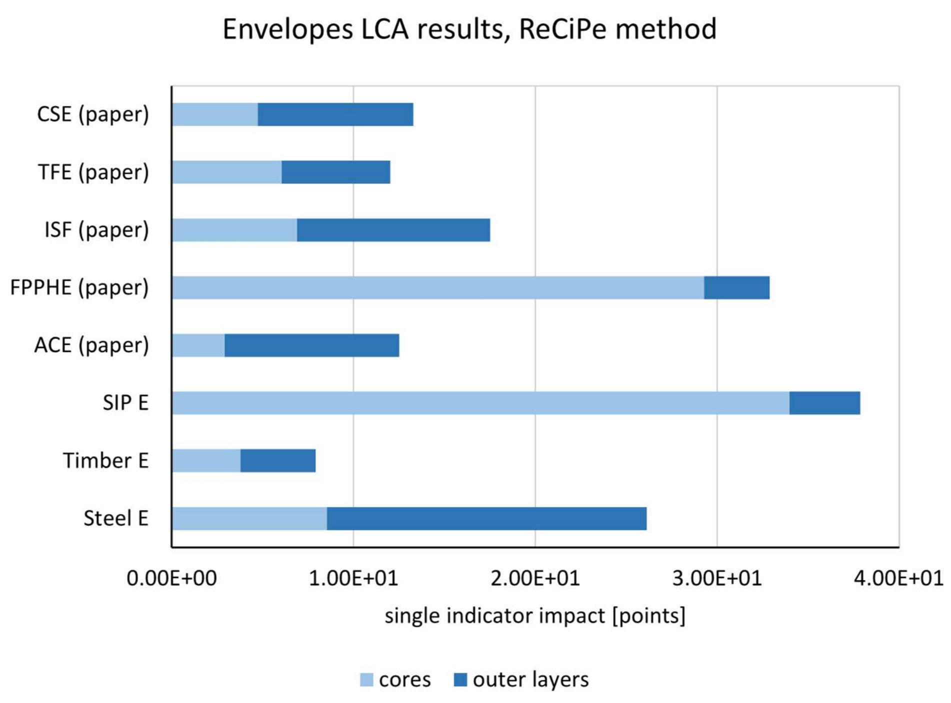


Figure 5.5. Envelopes LCA results - ReCiPe single-score indicator.

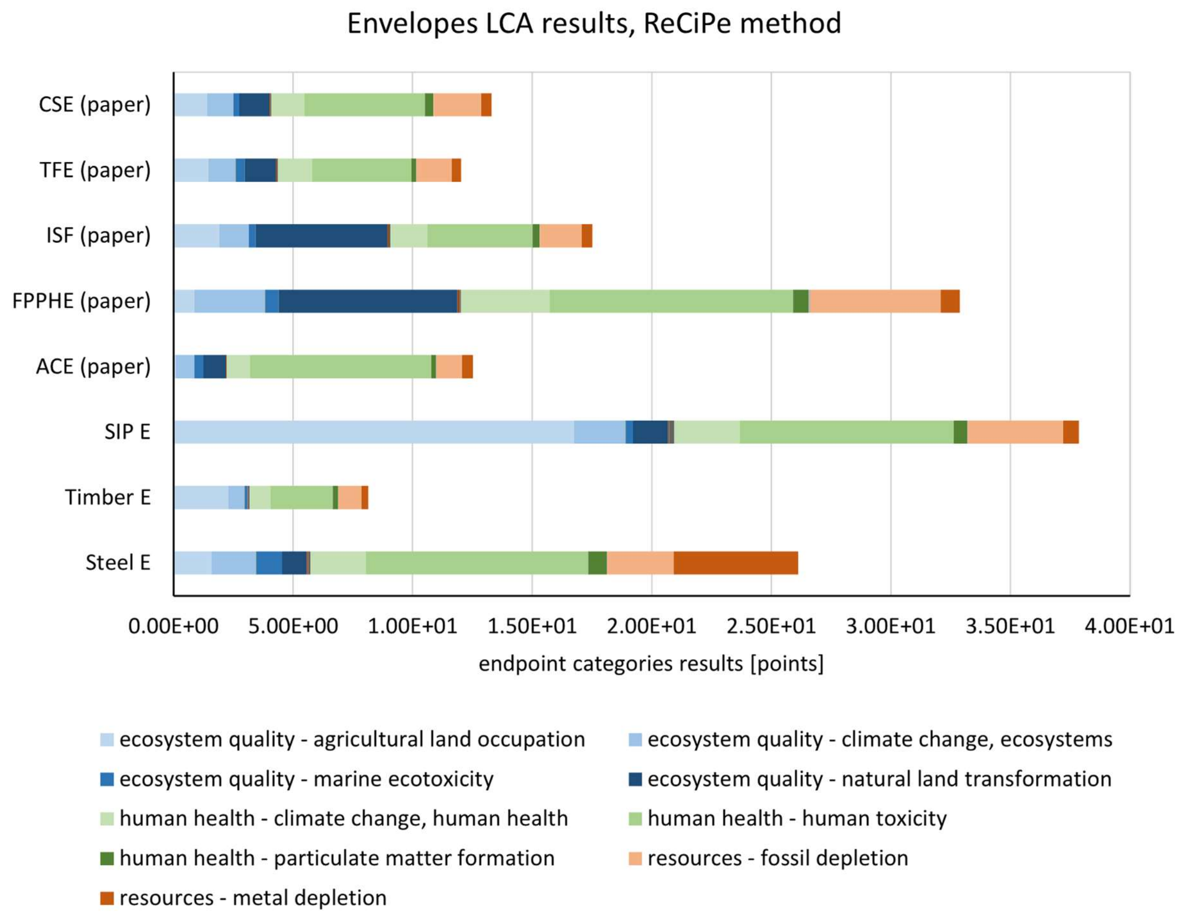


Figure 5.6. Envelopes LCA results - ReCiPe categories.

Considering LCA endpoint categories (see Figure 5.6), the biggest impact of paper-based envelopes is located in the areas of human toxicity, natural land transformation and fossil depletion. The SIP envelope has an important share of impact in the area of agricultural land occupation, while Steel one – in metal depletion. The results of midpoint analysis (see Figure 5.7) are generally consistent with endpoint indicators, although ACE presents a higher impact in metal depletion (due to aluminium frame) and SIP E in ozone layer depletion.

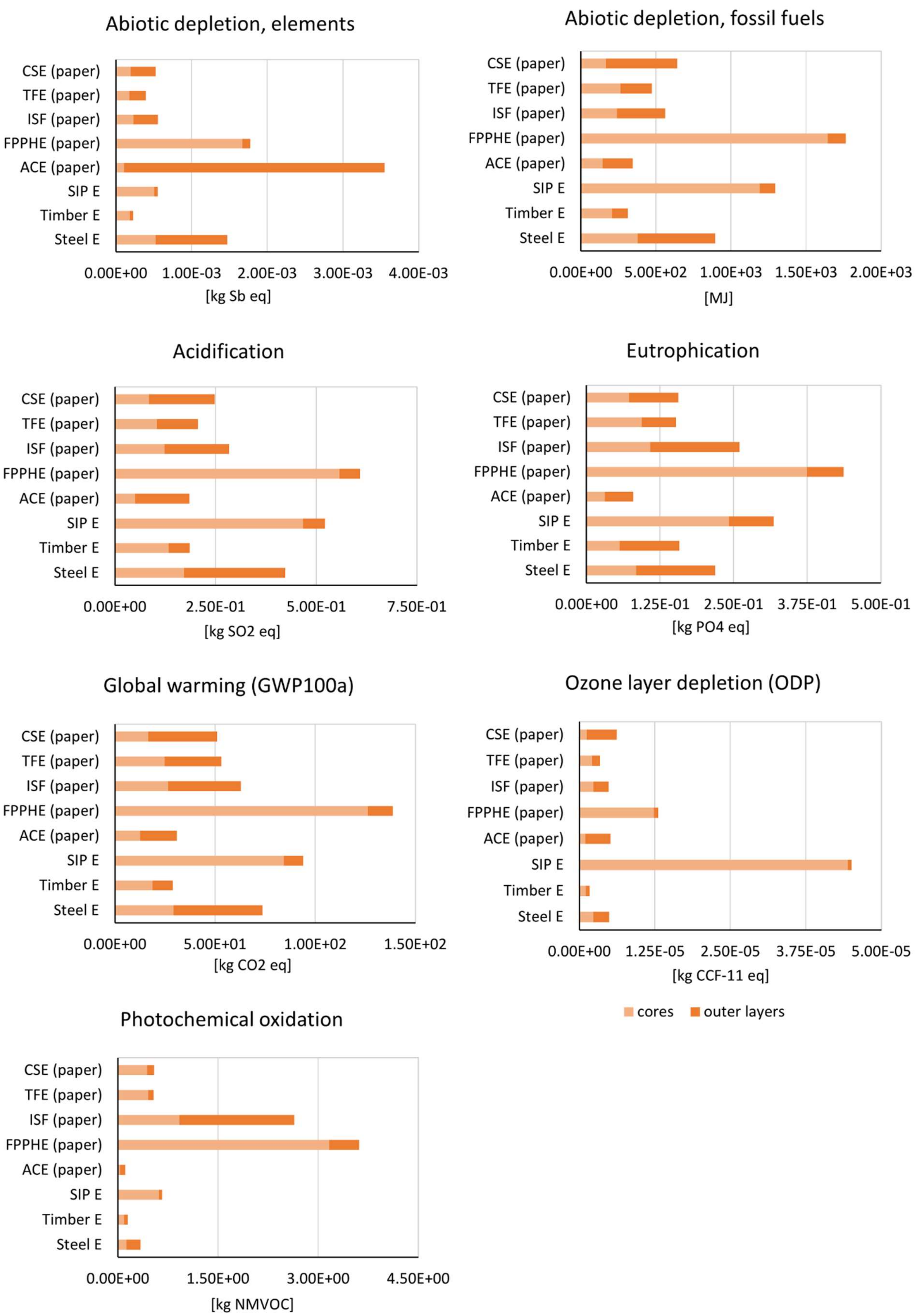


Figure 5.7. Envelopes LCA results - CML categories.

The complementary sensitivity analyses allowed for a deeper understanding of analysed cases. The abandonment of paper recycling in favour of landfill and the use of fresh fibre resulted in a 13% (for CSE) to 25% (for TFE) increase in the total LCA score of the envelope (see Figure 5.8). That corresponds with the results of Asdrubali et al. who reported a reduction in the EI of insulative panels made of recycled corrugated cardboard by approximately one-third in relation to fresh fibres cardboard, using the Eco-indicator method [78]. Moreover, paper is responsible for between 16% (ACE) and 81% (ISF) of envelopes' EI and adhesive – for 0.5% (ACE) to 44% (FPPHE). However, if the SBR adhesive in FPPHE was replaced with PVA one, the adhesive impact would be reduced by two-thirds, accounting for 17% of the envelope's impact.

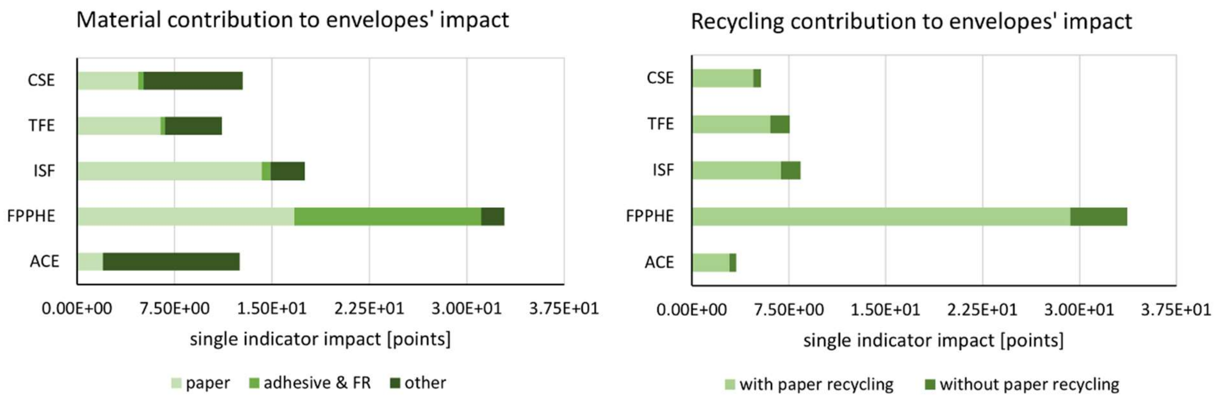


Figure 5.8. Envelopes LCA results - ReCiPe sensitivity analysis, (a) material contribution, (b) paper recycling contribution.

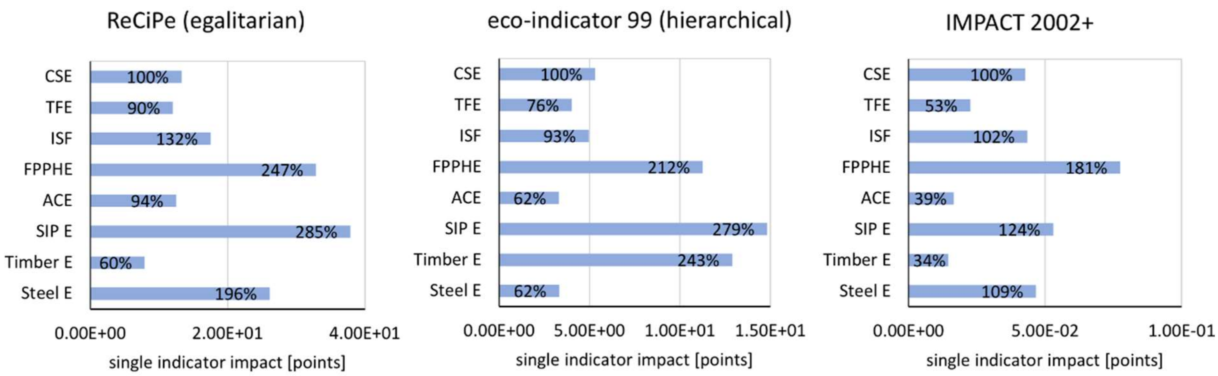


Figure 5.92. Envelopes LCA results - sensitivity analysis for assessment method.

In the method sensitivity analysis, the correlations between paper-based envelopes are rather similar, regarding the assessment method used. However, there are high differences in the results of non-paper case studies (see Figure 5.9). As part of further application work, comparative analyses should be carried out using specific manufacturing data unavailable at the design stage. Nevertheless, corroborating results of the best practice CML and ReCiPe methods provide a good basis for design analysis. It may be concluded, that each of the methods can be trusted for comparison between the paper-based envelopes.

Performance assessment

The second element of the analysis was the Performance Score, assessing the functional properties of the envelopes. The PS of the envelopes varies from 5 (ISF and FPPHE) to 19 (Steel E), and from 5 to 16 (TFE) in paper-based ones (see Table 5.3). As all of the analysed case studies present comparable thermal insulation properties (although different weights) the PS reflects mostly the durability of outer layers, which are highest in original paper-based (CSE, TFE) and Steel envelopes.

Table 5.3. Envelopes Performance Score.

	CSE	TFE	ISF	FPPHE	ACE	SIP E	Timber E	Steel E
U [W/m2K]	1	1	0	0	0	1	2	1
R:d ratio	1	1	0	0	1	1	2	2
R:m ratio	1	1	0	0	2	1	1	1
resistance to water	3	3	0	2	2	2	2	3
resistance to fire	3	3	2	1	1	2	2	3
resistance to mech. damage	3	3	1	2	1	3	3	4
price and material availability	2	4	2	0	4	2	4	4
Performance score	**15**	**16**	**5**	**5**	**10**	**12**	**16**	**19**

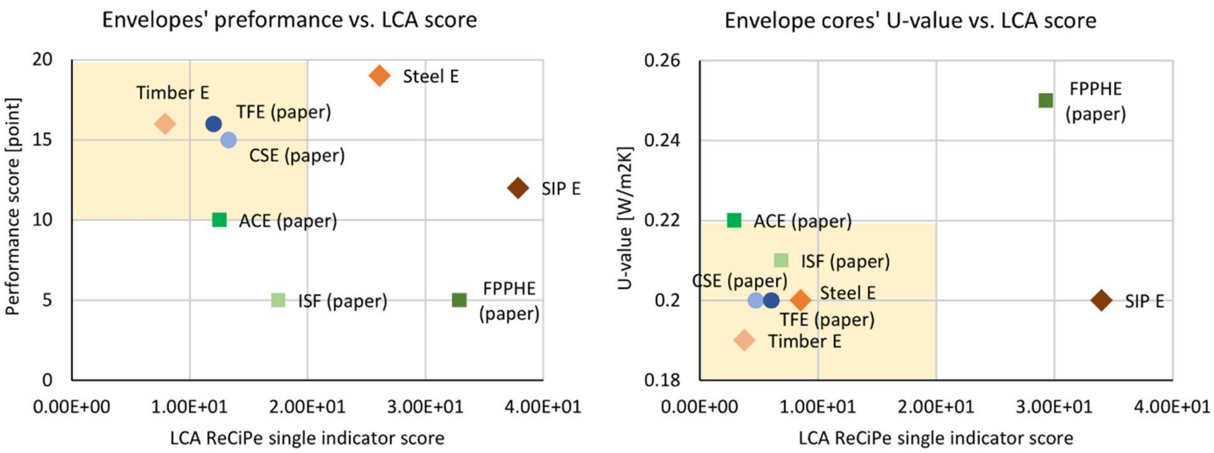


Figure 5.10. Envelopes and cores assessment.

Comparing PS and LCA (see Figure 5.10), the CSE, TFE and Timber E present the most optimal combination of characteristics, with a mid-range result of ACE envelope. However, in the cores' assessment, results are similar for the majority of cases, excluding FPPHE and SIP E, which caused significantly higher EI. That leads to the conclusion, that for non-sandwich paper-based cores, the most significant impact differences arise from outer layers, which are exchangeable between the envelopes. Based on the conducted LCA and PS research, it was found that the favourable characteristic of a paper-based envelope may be achieved by combining the ACE of CFE core with TFE outer layers. Although mechanical properties are outside the scope of the study, it should be noted that the mechanical strength of the CFE core exceeds the strength of the ACE core, therefore the combination of the CFE core and TFE outer layers can be recommended as a result of the study.

5.4. Findings

Chapter 5 presented two novel paper-based envelope designs, prepared based on research described in previous chapters. These envelopes constitute one of the most important outcomes of the presented thesis. The research conducted in this chapter analysed the environmental benefits and potential risks associated with the use of building envelopes made mostly with paper components, such as corrugated cardboard or paperboard, including the original designs of CSE and TFE. Replacement of conventional envelopes with paper-based ones, especially in buildings with a limited lifespan, may reduce their embedded environmental impact, as well as the amount of waste generated, due to the high recycling potential of paper. Most of the paper-based designs overperform conventional SIP-panel and steel frame building envelopes in terms of environmental impact, confirming the relevance of their real-life application.

Answers to research questions

Q1: Can the proposed CSE and TFE provide an environmentally friendly alternative to envelopes made of conventional building materials?

A1: The conducted research showed, that the environmental impact of CSE and TFE is significantly lower than EI of standard SIP panels and steel frame envelope, and similar to the EI of timber frame envelope. Furthermore, CSE, TFE and timber envelope presented a favourable balance between functional and environmental properties. Thus, the proposed paper-based envelopes may provide an environmentally friendly alternative for the assembly of small-scale buildings.

Q2: Which factors have the biggest influence on the environmental impact of paper-based envelopes?

A2: Various factors may significantly influence the environmental impact of paper-based building envelopes. According to obtained analysis results, some of the most important aspects are type of structure (with a preference for embedded frame), efficiency of insulative material used, share of recycled fibres in paper components (preferably 100% recycled), materials recycling strategies, adhesive consumption, impregnating and coating agents used, and cladding materials chosen.

Chapter 6

Implementation – building

In the last stage of the research, a selected paper-based building envelope was implemented into a building design. The prototypes of both envelopes form Chapter 5 were constructed to prove the concept and test the feasibility of the proposed designs (see Figure 6.1). A representative section of each envelope, with dimensions of 2x2 m, was constructed, including structural elements, insulative boxes, outer layers and connections between them. Due to the technical difficulties of blowing cellulose of a certain density into honeycomb boxes and the availability of materials, the Tube Frame Envelope was chosen for the final design.

6.1 Structure

The whole structure of the proposed building is based on the Tube Frame Envelope, in which load-bearing elements of walls, roof and floor are connected, forming structural frames (see Figure 6.2). The external walls are made of the TFE as presented in Chapter 5, while the roof and floor are made of TFE and given an additional 5 cm thick BC-flute corrugated cardboard layer, to meet thermal insulation requirements of U_{max}=0.15 W/m^{2}K. The external outer layer of the roof is protected with steel roofing panels on OSB sheathing instead of fibre-cement boards, while the floor is finished with plywood.

The building structure consists of repetitive pentagonal structural frames, placed on three parallel foundation beams, at 120 cm intervals (see Figure 6.2). Each frame is composed of five segments of paper tube-honeycomb beam from TFE. Segments are connected by timber tenons placed inside the tubes and screwed with steel elements (see Figure 6.3). Spaces in between frames are filled with corrugated cardboard insulation boxes. Corners and joint areas are insulated with additional corrugated cardboard elements, to avoid thermal bridges. Outer layers are attached on both sides of each wall, floor and roof, with an air cavity under the façade.

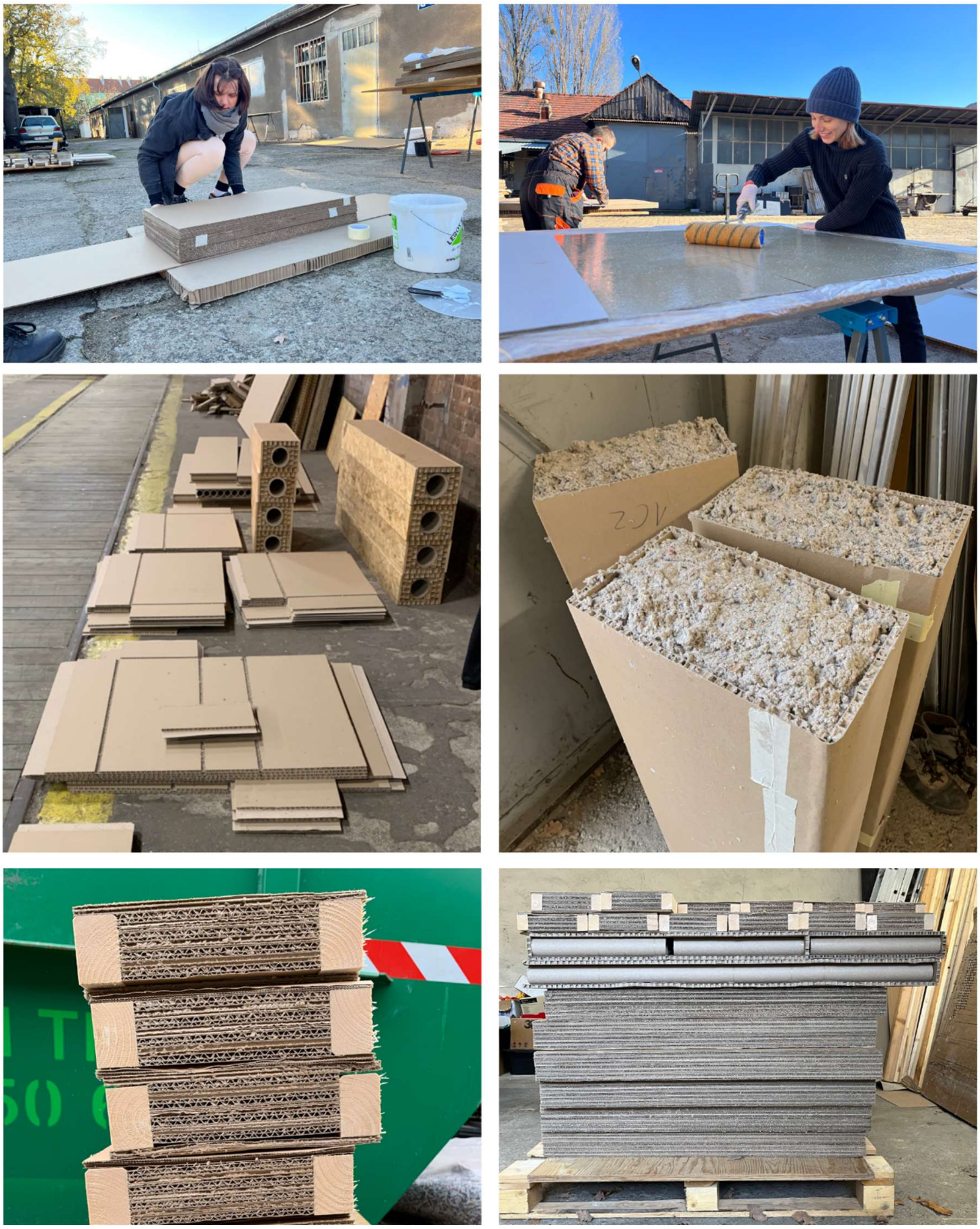


Figure 6.1. TFE and CSE prototyping process. [35]

[35] Photos by J. Łątka.

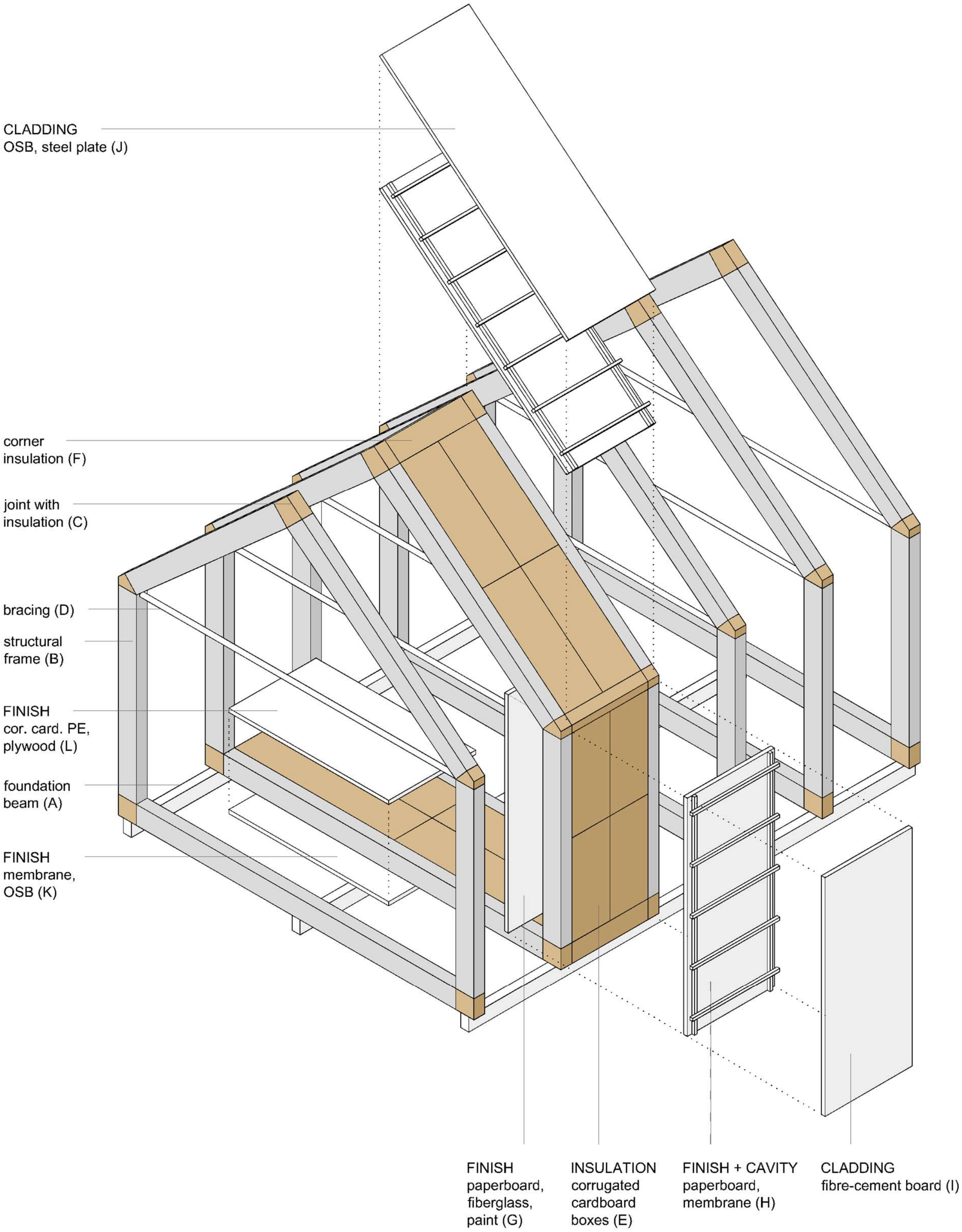


Figure 6.2. Axonometric view of the paper-based building structure based on TFE.

The whole TFE building structure consists of 274 prefabricated elements in 22 repetitive types, represented by parts A-L in Figure 6.2. All the components are connected with mechanical joints (bolts and screws), thus they may be disassembled, replaced or reused in other structures.

The elements of the TFE structure are as follows.

- 3 timber foundation beams (A);
- 30 segments of paper tube beams from the TFE system, forming 6 structural frames (B), including 12 for the roof part, 12 for external walls and 6 for the floor;
- 30 frame segments joints (C), each consisting of two timber tenons and steel connector (see Figure 2.3), with corrugated cardboard insulative blocks, including 12 for a wall-floor corner, 12 for a roof-wall corner and 6 for a roof ridge;
- 6 frame bracing (D) made of paper tubes;
- 100 corrugated cardboard insulative boxes (E), including 40 for the roof part, 40 for external walls and 20 for the floor;
- 25 corner insulation blocs (F) made of corrugated cardboard, including 10 for a wall-floor corner, 10 for a roof-wall corner and 5 for a roof ridge, while the latter two also include timber struts connecting the frames;
- 20 indoor finishes (G), including 10 for walls and 10 for the roof, consisting of FR paperboard laminated with PVA adhesive and painted fibreglass mat (see layer I4 in Chapter 4.2. and TFE in Chapter 5);
- 20 outdoor external wall finishes (H), including 10 for walls and 10 for the roof, consisting of FR paperboard laminated with dextrin adhesive, breather membrane, timber battens and counter battens, and corrugated cardboard insulation layer for roof elements (see layer E2 in Chapter 4.2. and TFE in Chapter 5);
- 10 external wall cladding (I), made of fibre-cement boards (see layer E2 in Chapter 4.2. and TFE in Chapter 5);
- 10 roof cladding (J), made of aluminium sheet (standing seam roof panels) on OSB board sheathing (see layer E5 in Chapter 4.2.);
- 10 floor outdoor (bottom) finishing layers (K), consisting of breather membrane and OSB board with varnish coating;
- 10 floor indoor (top) finishing layers (L), consisting of corrugated cardboard insulation layer, polyethene (PE) foil and plywood with varnish coating.

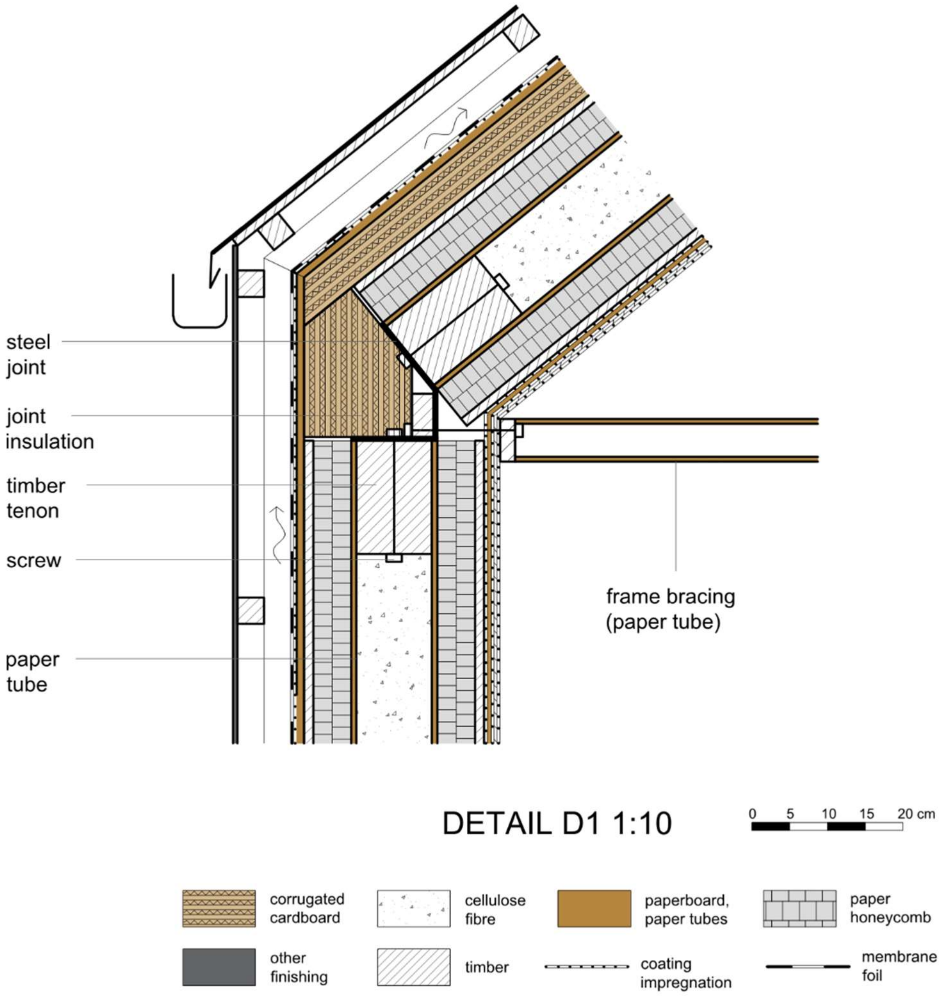


Figure 6.3. The connection between wall and roof sections of the structural frame.

Building process

Only basic equipment is required to assemble the entire structure (drill, spanners, ladder) and none of the elements weight exceeds 50 kg, so they can be safely carried by two people. The assembly process should start with levelling beams (A) on chosen foundations (ground screws, concrete feet or slab with anchors). Secondly, frame segments (B) and bracing (D) are mounted and connected with joints (C). Next, the envelope is assembled in the following order: floor layers (K, E and L), floor-wall corner insulation (F), wall and roof inner finishes (G), wall and roof insulation boxes with corner insulations (E and F) and wall and roof outer finishes (H). Claddings (I and J) are mounted in the last step of the construction process. Due to a high level of components prefabrication, a structure of the proposed size should be buildable within one working day.

6.2. TFE Cardboard House design

To implement the proposed envelope, a small, full-performance housing unit, that may serve as a dwelling or holiday house, was designed. Single-family houses and individual recreation facilities can, according to the Polish building code, be designed from materials without fire-resistant certification. Therefore, the proposed house could be legally prototyped.

Form

A form chosen for the House was an archetypical shape of a single-duct building with a gable roof with a pitch of 40 degrees. A simple outline shape reduces energy losses through the envelope and a pitched roof reduce the risk of leakage or excessive snow load, which is especially important for water-sensitive structures. Moreover, the form chosen is one of the most commonly used in the small-scale architecture of Poland, thus it enables the opportunity to fit into the urban context in many locations.

Function

The housing unit, with a construction area of 34.30 m^2, provides a living space for two people. The house consists of a ground floor with usable space of 26.34 m^2, and a mezzanine under the pitched roof, supported on internal partition walls. The living space with a kitchenette and bathroom is located on the ground floor, while the mezzanine provides sleeping space. A plan view of the TFE Cardboard House is presented in figure 6.4, its section in Figure 6.5 and the selected parameters in Table 6.1. Due to the universal functional layout, the House may serve as a single-family dwelling, emergency or temporary housing (for homeless people, refugees, victims of natural disasters etc.), as well as a private holiday home, allotment house or resort bungalow.

The proposed TFE Carboard House presents a representative example of o full house structure composed of the envelope proposed in the thesis. The design features joints, foundations, bracing and a façade ventilation system. The structural system may be enlarged or multiplied to form buildings in various sizes and shapes.

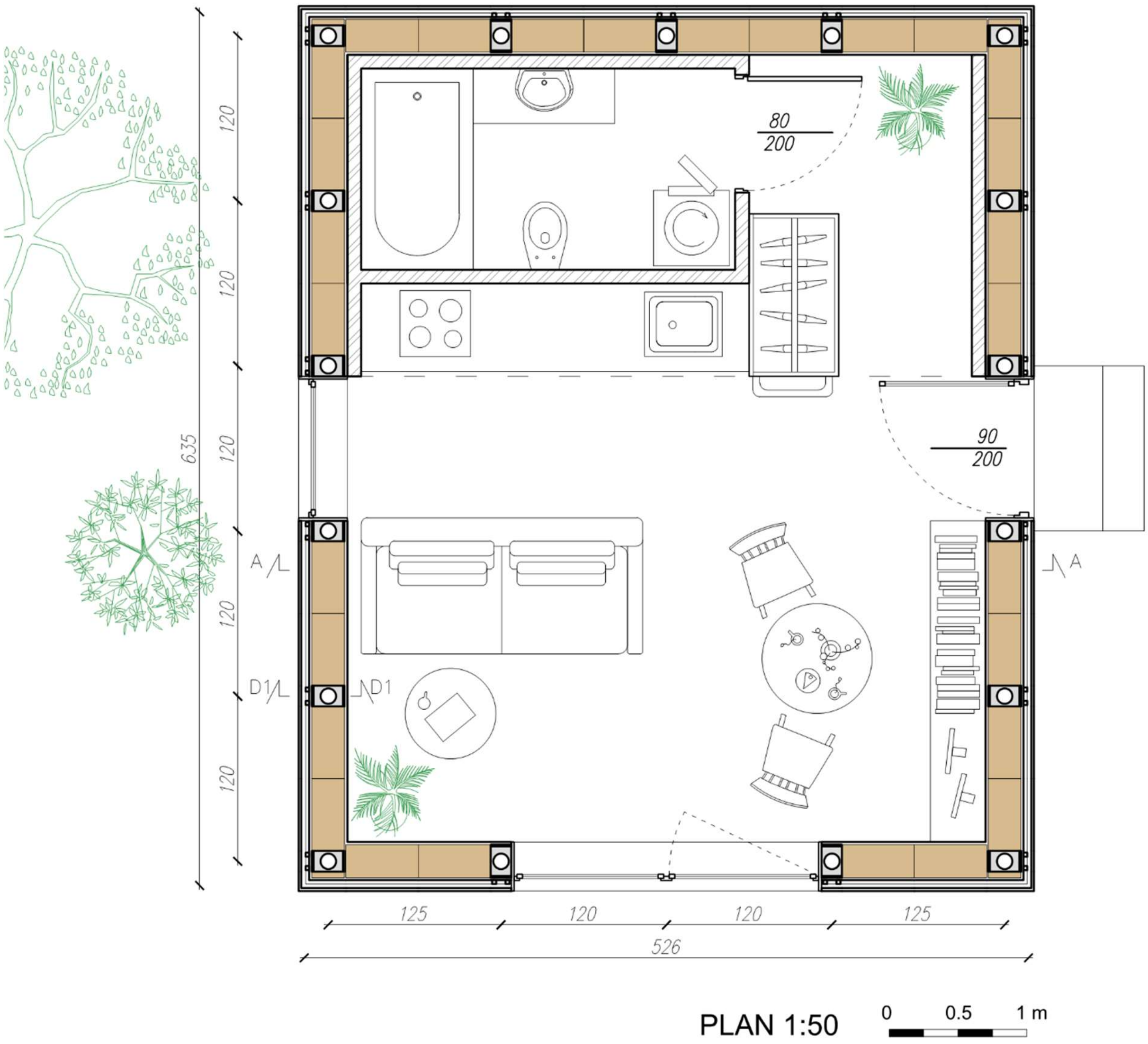


Figure 6.4. Ground floor plan view of the TFE Cardboard House. [36]

[36] Based on drawing by D. Jezierska.

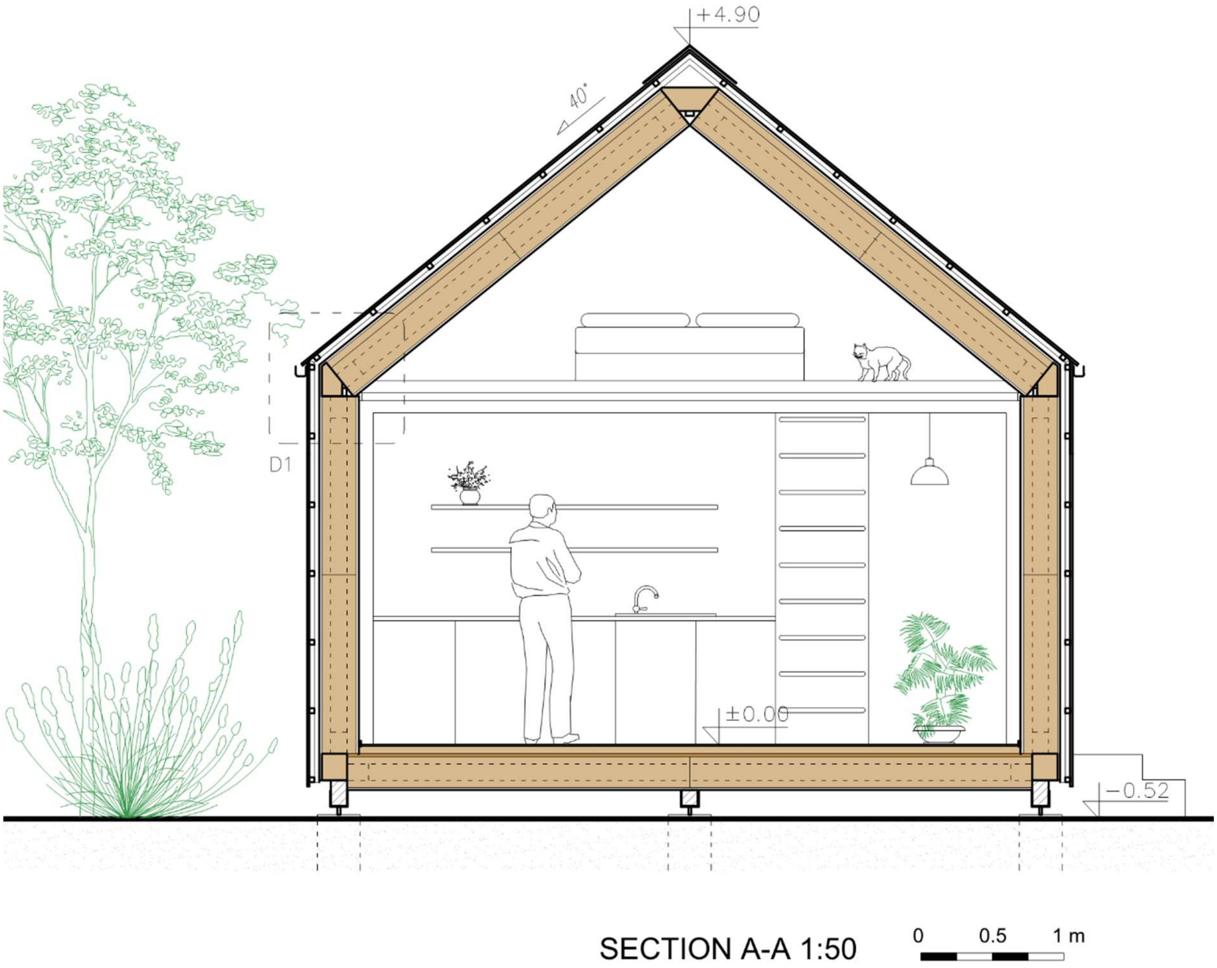


Figure 6.5. Section A-A of the TFE Carboard House. [37]

Table 6.1. Selected parameters of the TFE Cardboard House.

Parameter	**Value**
Construction area	34.30 m^2
Usable floor space	26.34 m^2 + 10.82 m^2 on mezzanine
Usable volume	90 m^3
Area of wall panels	39.00 m^2
Area of floor panels	26.49 m^2
Area of roof panels	36.00 m^2
Estimated structure weight	6000 kg

[37] Based on drawing by D. Jezierska.

Chapter 7

Conclusions

The presented dissertation discussed the possibility of using paper-based materials as components of environmentally friendly building envelopes. In Chapter 2 the State of the Art in paper-based architecture and envelopes was reviewed, while in Chapter 3 water protection, fire protection and lamination techniques were tested. Based on the obtained results, six envelope cores along with fourteen outer layers were proposed and evaluated in Chapter 4. As a result, two novel full-performance paper-based building envelopes were presented in Chapter 5 and compared to envelopes made of conventional materials in terms of environmental and functional performance. Finally, the selected envelope was implemented to a housing unit in Chapter 6.

Conducted research led to the conclusion, that during the design process of sustainable paper-based building envelopes particular attention should be drawn to the following aspects.

- Structure type – sandwich envelope lead to increase in EI, while row structures tend to form thermal bridges at the junction of the load-bearing elements, thus the use of embedded frame can be recommended.
- Amount and type of adhesive – although the use of adhesives seems unavoidable, the amount should be limited, e.g. by spot gluing or partial replacement by other joining techniques. Furthermore, the type of adhesive plays an important role, and PVA glue usually provides a favourable balance between strength and EI.
- Ventilated façade system – the efficient evacuation of moisture that may occur inside a core during use is essential for structure safety and thermal insulation properties. Even a small increase in moisture can lead to a loss of strength or biological corrosion. Ventilation can be improved by means of a diffusion gradient, e.g. achieved with different types of adhesives.

- Outer layers and protection techniques – protection against water, fire and mechanical damage is a key element of every paper-based building component. However, finishing materials, coatings and impregnants may increase the envelope EI even several times. Designers should choose materials with an optimum balance between EI and durability, taking into account the requirements for a specific construction.

Table 7.1. SWOT analysis for paper-based envelopes.

Strengths	**Weaknesses**
Low environmental impact Relatively low cost Material availability and manufacturing unification High thermal insulation properties Supports a healthy indoor climate	Sensitivity for an increase in environmental burden due to design decisions Prone to water and mechanical damage Requires fire protection Limited application of mechanical joints Low thermal mass
Opportunities	**Threads**
Demand for environmentally friendly building components Decrease in average life-span of buildings Demand for temporary and emergency buildings, and buildings' flexibility Development and technological advances in the paper industry and recycling	Lack of social trust Building code restrictions Lack of standardised data about paper components

Considering the advantages and disadvantages presented in the SWOT analysis (see Table 7.1) it may be concluded, that paper-based building envelopes may be the appropriate solution to various needs of the construction industry. The envelopes provide sustainable yet affordable building components, fitting into the increasing demand for temporary, prefabricated and flexible buildings. However, many constraints need to be overcome before wider-scale implementation, including building code regulations, lack of standardised data for static analysis and lack of social trust. Thus, further and broader research, especially in natural conditions, is required, that will allow paper to be legally recognised as a building material.

7.1. Goals fulfilment and hypothesis confirmation

The research conducted allowed for the fulfilment of all the goals G1-G8 set at the beginning of the thesis. A graphical representation of goals in relation to the proposed building envelopes is presented in Figure 7.1.

G1 Goal 1. To review the state of the art in paper-based products in architecture applications, summarise their characteristics and indicate knowledge gaps.

Goal 1 was met by reviewing databases of scientific articles and literature in subchapter 2.1. Over 150 references, including scientific articles, books, reports and standards were selected and included in the state of the art. Based on literature data, basic characteristics regarding mechanical, thermal, acoustic and environmental properties of paper-based products were provided, as well as impregnation and joining techniques. Knowledge gaps in the area of water, fire protection, lamination and environmental impact were indicated and addressed in the subsequent parts of the thesis.

G2 Goal 2. To analyse and compare literature-based paper-based building envelopes.

Goal 2 was met by reviewing the literature-based paper building envelopes which met the minimum criteria set. In subchapter 2.2. ten envelopes from the years 2001-2021 were presented with detailed sections and characteristics, including thermal properties, durability, dimensions and materials used. The envelopes were classified into three categories based on structure type – sandwich, row and embedded frame. The conclusions drawn from the review were later incorporated into the design process.

G3 Goal 3. To develop water protection techniques for paper-based envelope elements that do not compromise the environmental properties of the material.

Goal 3 was met by conducting immersion and high humidity tests on impregnated paperboards in subchapter 3.1. A set of biodegradable, oil-based and wax-based impregnants and the coatings was tested alongside conventional varnishes. It was observed, that a combination of oil-based and wax-based impregnants provid a high level of protection against water and vapour. Selected impregnation techniques were used in the design process in Chapter 4.

G4 Goal 4. To develop fire protection techniques for paper-based envelope elements that do not compromise the environmental properties of the material and that can be combined with water-protecting impregnation.

Goal 4 was met by conducting a series of single-flame ignitability tests on impregnated paperboard specimens in subchapter 3.2. The specimens were coated with fire retardants based on borates and phosphorates, water coatings from previous tests or a combination of both types of protection. The tests confirmed, that FR precoating significantly decreases the ignitibility of flammable oil-based and wax-based waterproofing impregnants. Selected impregnation techniques were used in the design process in Chapter 4.

G5

Goal 5. To develop paper lamination techniques that provide stable joints without significantly increasing components' environmental impact nor hindering the paper recycling process.

Goal 5 was met by conducting tensile tests on single-lap adhesively bonded paperboard specimens in subchapter 3.3. A set of PVA, dextrin and synthetic rubbed adhesives were tested in several adhesive layer thicknesses. Based on both tensile test results and Ease of Handling assessment PVA adhesives were recommended for use in the design process.

G6

Goal 6. To propose original designs of paper-based envelope cores, that provide structural stability, thermal insulation required by Polish building code regulation and low environmental impact.

Goal 6 was met by designing and evaluating six novel paper-based envelope cores in subchapter 4.1. The cores, designed on the basis of state of the art review and experimental works conducted in the previous part of the research, feature efficient thermal insulation, and various types of structural elements with reduced thermal bridges. All of the designs met the requirement of U_{max}= 0.20 W/m2K. According to the LCA analysis, the embedded frame structures coursed the lowest environmental burden and thus were selected for final designs.

G7

Goal 7. To propose original designs of paper-based envelope outer layers, that provide protection against weather conditions, water, fire and mechanical damage while maintaining low environmental impact.

Goal 7 was met by designing and evaluating fourteen novel protective outer layers for paper-based envelopes in subchapter 4.1. All of the proposals provide protection against weather conditions, water, fire and mechanical damage, suitable for outdoor or indoor spaces. Based on both LCA results and the Performance Score assessment a set of outer layers was chosen for incorporation into the final design.

G8

Goal 8. To assess the relevance of the proposed paper-based envelopes application as a pro-ecological alternative to literature-based paper envelopes and envelopes made of conventional building material.

Goal 8 was met by designing two full-performance paper-based building envelopes in Chapter 5. The proposals were based on selected cores and outer layers designs evaluated in the previous chapter, with minor improvements. The envelopes were compared to three representative literature-based paper envelopes and three envelopes made of conventional building materials. Based on conducted LCA analysis and Performance Score assessment it was concluded, that the proposed paper-based envelopes present functional and environmental performance comparable to timber stud envelopes and superior to all the other analysed case studies.

G9 Goal 9. To propose implementation of the selected paper-based envelope into a small-scale building.

Goal 9 was met by designing a small-scale paper-based building in Chapter 6. The proposal incorporates a selected paper-based building envelope designed in previous chapters – Tube Frame Envelope. The envelope was selected based on research and prototyping process results. The designed basic housing unit present a structural system that may be multiply or enlarged to create various types of buildings.

Results obtained in the research and achievement of all the specific goals allow for confirmation of the hypothesis formulated in the introduction to the thesis, that:

A full-performance building envelope with favourable environmental characteristics may be designed from paper-based components.

7.2. Limitations of the study

Although the thesis presented comprehensive knowledge regarding the design of paper-based envelopes, it has its limitations that need to be mentioned for the credibility of the information provided.

First of all, generic data had to be used in several stages of the research, due to the lack of more specific data sources. While parameters like type of paper or material weight were provided by the industry, others, for example, thermal conductivity, were obtained from literature, thus they may differ from actual values. Moreover, parameters may slightly differ depending on the manufacturer and place of production.

Furthermore, the LCA analysis was performed based on generic data from the Ecoinvent database and excluded impacts generated during construction, use and demolition stages. The analyses were conducted ensuring the highest reliability of the results in respect of the available data. However, the interpretation of the results, which are subject to a greater risk of bias due to data quality, should be undertaken with caution.

Finally, the proposed envelopes have not been evaluated in natural conditions yet. Although the proposals were evaluated in computer simulations and small-scale prototypes, only a full-scale prototype will allow for a comprehensive, real-life assessment.

7.3. Future research directions

The ideas, designs and results presented in this thesis may be potentially extended in the following directions.

- The proposed envelopes may be prototyped and tested in real-life conditions, in the form of an experimental housing unit. The structure should be monitored for thermal insulation, thermal bridges, air-tightness, acoustic properties, structural stability under long-term stress and resistance to weather conditions.
- The scope of envelopes Life Cycle Assessment analysis may be extended to include impacts generated in the use and demolition phases and specific data regarding the production process. However, such analysis would only be possible if the housing unit test series was produced and inhabited, allowing for data collection.
- The use of speciality papers (e.g. fire resistant or water repellent) may be considered, as well as the use of adhesives, impregnates and coatings designed specifically for use on construction paper.
- The acoustic and mechanical properties of the proposed envelopes may be evaluated.

Research presented in this thesis will be further developed within the *Transportable, Eco-friendly Cardboard House* project, which will conclude with the construction and evaluation of a paper-based housing unit prototype.

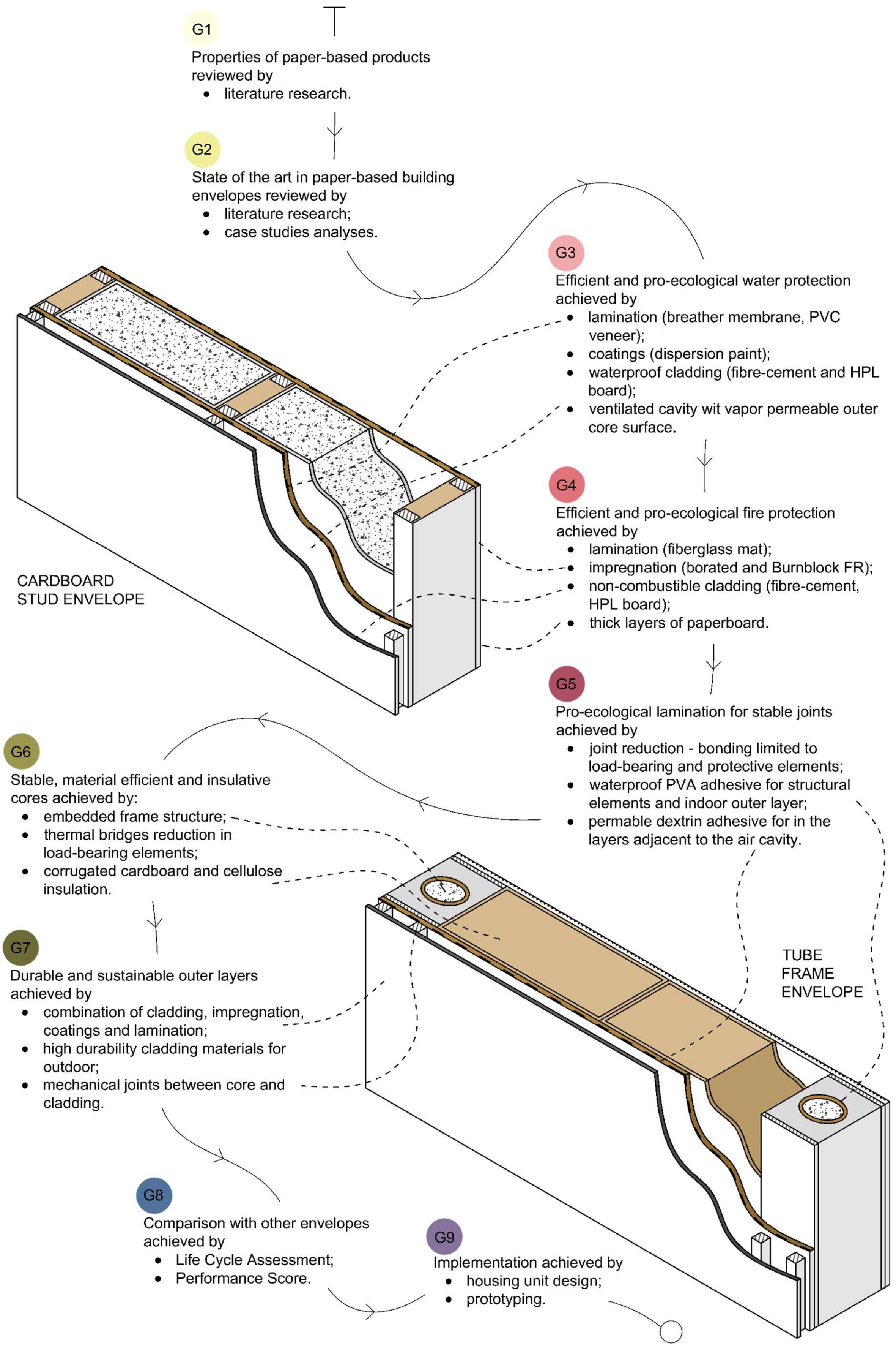


Figure 7.1. Scheme of achievement of goals by proposed paper-based building envelopes.

Curriculum Vitae

Agata Jasiołek

Researcher in the field of architecture and urban planning, PhD candidate at Wroclaw University of Science and Technology. Scientific and professional interests related to building environmental assessment and the use of paper as a building material, especially in building envelope. Author and co-author of experimental paper-based prototyping projects, scientific journal articles and international conferences presentations.

Education

From 10.2019	Doctoral School, Wroclaw University of Science and Technology
02.2018-07.2019	MSc in Architecture, Wroclaw University of Science and Technology
10.2014-02.2018	BSc in Architecture, Wroclaw University of Science and Technology

Research and academic experience

From 03.2021	expert in paper architecture in "Transportable Eco-friendly Cardboard House – R&D works on implementation of cellulose-based materials in architecture" research project at WUST, founded by NCBR Lider grant
05-07.2021	guest researcher at the Institute of Structural Mechanics and Design of TU Darmstadt, Germany
08-10.2018	researcher and designer in "Transportable Emergency Cardboard House (TECH_04)" project, founded by the EIT Climate-KIC Greenhouse grant

Teaching experience

From 03.2020	teaching and co-teaching design courses at the Faculty of Architecture, Wroclaw University of Science and Technology: industrial building design, housing design, ProtoLAB design&build
07.2019	tutor at the international design and build Summer Schools of Architecture workshops, Wrocław, Poland
07-08.2022	tutor at the international students workshops ProtoLAB design and build, Wrocław, Poland
From 04.2022	tutor at the University of Universities international online workshops
From 11.2018	president (11.2018-10.2020) and supervisor (since 05.2022) of the Humanisation of the Urban Environment students' science club at WUST

Publications

A. Jasiołek, P. Noszczyk, and J. F. Łątka, "Paper-based building envelopes – Thermal and environmental properties of original envelope designs," Energy and Buildings, vol. 289, 2023 *(IF 7.201; MEiN 140 pt)*

J. F. Łątka, A. Jasiołek, et al., "Properties of paper-based products as a building material in architecture – An interdisciplinary review," Journal of Building Engineering, vol. 50, no. January, 2022, *(IF 7.144; MEiN 140 pt)*

M. Brzezicki and A. Jasiolek, "A Survey-Based Study of Students' Expectations vs. Experience of Sustainability Issues in Architectural Education at Wroclaw University of Science and Technology, Poland," Sustainability, vol. 13, no. 19, 2021, *(IF 3.889; MEiN 100 pt)*

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A. Jasiolek, J. Latka, and M. Brzezicki, "Biodegradable methods of impregnating paperboard for its use as a building material," Int. Journal of Sustainable Engineering, vol. 14, no. 5, 2021, *(MEiN 70 pt)*

A. Jasiołek, "Preliminary report on ignitibility of combined pro-ecological waterproofing and fire retardant coatings for paperboard in architectural application," Architecture Civil Engineering Environment, vol. 15, no. 4, 2022, *(MEiN 70 pt)*

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Publications in the review process

A. Jasiolek, "Paper-based building envelopes – environmental and performance assessment of original and literature-based designs," Building and Environment, 2023, *(IF 7.093; MEiN 200 pt)*

A. Jasiolek, A. Wolf, N. Bishara, P.L. Rosendahl, "Adhesive paperboard connections in architectural applications: modelling, characterization, and performance assessment," International Journal of Adhesion and Adhesives, 2022, *(IF 3.848; MEiN 100 pt)*

A. Jasiołek, J. Gromek, Sz. Misiurka, J. F. Łątka, „Environmental and performance assessment of protective outer layers for low-carbon paper-based building envelopes," Architectural Engineering and Design Management, 2023, *(MEiN 100 pt)*

Conference presentations

J. Łątka, A. Jasiołek, "TECH 04 – Transportable Emergency Cardboard House gen. 4 th. Research and development of the cardboard emergency shelter", ACPS 2021: Architecture, City, People, Structure, 2021, Wrocław, Poland

A. Jasiołek, "Preserving environmental properties in paper-based architecture", International Conference on Structures and Architecture (ICSA 2022), 6-8.07.2022 Aalborg, Denmark

A. Jasiołek, S. Misiurka, "Bonding and protecting paper-based building elements vs. the ecological impact", Innovative Structural Systems in Architecture (ISSA2021), 2021, Wrocław, Poland

A. Jasiołek, "Środowiskowa ocena cyklu życia produktu (LCA) jako narzędzie wspierające projektowanie architektury zrównoważonej", ArchReSci, 2023, Wrocław, Poland

Patent applications

04.2023	A. Jasiołek, et al., “Load-bearing wall element of a frame building”
04.2023	A. Jasiołek, et al., “Load-bearing beam of frame building”

Grants, scholarships and awards acquired

04.2023	Secundus Arard for best publishing young scientists at WUST
11.2022	Jan Mozrzymas Scholarship for interdisciplinary research, Wrocławskie Centrum Akademickie
09.2020	“Transportable Eco-friendly Cardboard House – R&D works on implementation of cellulose based materials in architecture”, Lider XI grant, The National Centre for Research and Development, led by J. Łątka
10.2020	Short-Term Research Grant from German Academic Exchange Service (DAAD), for a 3-month research stay at TU Darmstadt

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List of Figures

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