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Examining Cardboard as a Construction Material for Sustainable Building Practices in Lima, Peru

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Abstract: This research work aimed to analyse the impact and potential of cardboard as a construction material, as well as cultural aspects and sustainable construction regulations, in the context of Lima, Peru. The study employed a mixed research methodological approach, including three case studies from Japan, the Netherlands, and the UK, online interviews, and surveys with British, Polish, and Peruvian architects. Additionally, a range of dynamic thermal simulations of an existing school building in the UK employing cardboard construction material were conducted to evaluate its impact on energy consumption. The survey revealed that there is a gap in information about the material applied to the architecture and construction environment, which is coupled with a general distrust and little credibility regarding its inclusion. However, cardboard is also seen as a complementary material in hybrid construction systems, with potential recycling enhancing environmental sustainability. The case studies showed cardboard structures can fulfil different functions with flexible designs that are adaptable to different contexts, simple, economical, accessible, recyclable, and capable of resisting natural disasters. However, post-construction consequences affect the structural integrity. Simulations carried out with EnergyPlus confirmed that cardboard has an optimal performance that can be a great complement or variation to traditional materials to reduce the carbon footprint and could meet the U-value requirements established in the construction regulations. Since it has low thermal conductivity and good acoustic insulation, it is recyclable and generates fewer CO_2 emissions, and it is economical, accessible, versatile, and light in use. For example, from a technical point of view, when used as thermal insulation, this element outperforms other conventional materials due to its cellular structure, which traps air, a poor conductor of heat. This study provides a set of guidelines for sustainable building practices. Such guidelines can be adopted to produce a prototype of a sustainable building using cardboard as the main construction material to contribute to the current debates on the state of building materials. It offers valuable perspectives on the development of building materials, construction techniques, and building regulations that can guide the way forward for sustainable building practices in the future, informing policymakers and building designers about construction techniques that adhere to building codes and lessen the built environment's environmental impact.

Keywords: cardboard; architecture; prototype; experimental design; construction materials; sustainability; simulations; energy efficiency; case studies; Peru

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1. Introduction

In the context of the growing concern for sustainability in architecture, exploring innovative alternatives that contribute to mitigating climate change, particularly through materials and construction systems, becomes increasingly compelling. In this regard, cardboard emerges as a material of special interest due to its significant sustainable potential. It is a natural, readily accessible, strong, flexible, adaptable, economical, recyclable, reusable, and environmentally friendly material [1]. Nevertheless, there is a notable gap in the amount of research, knowledge, and implementation.

Cardboard's origin dates back to 105 A.D. in China [2], and since then, it has evolved across different cultures and generations worldwide. Today, it is ubiquitous in our daily lives in various forms, such as books, packaging boxes, and countless other applications. However, its use in the construction industry remains rare [3].

This study gathered information on the use of cardboard in architecture as a construction material through a literature review encompassing the material's history, production, and properties. Additionally, the contextual feasibility of Lima, the capital of Peru and a major city in South America, was analyzed. Lima is known for its biodiversity and historical, cultural, and gastronomic richness, and it serves as an economic and political centre [4]. However, it also faces various challenges and issues, such as the general instability that has characterised the country, and its main "cancer" is corruption [5], and the corruption hat exists in the region, which is one of the highest in Latin America, with Peru having a percentage of 73.9% [6].

There is a strong conviction and vision that cardboard can be successfully used as an architectural material in Peru, presenting it as an evolution and/or alternative to traditional methods and materials. Given the substantial potential of this sustainable material, supported by evidence from various case studies worldwide, there is, however, a significant gap to address, requiring further research on the subject.

Therefore, the primary aim of this research was to examine cardboard as a construction material for sustainable building practices with reference to Lima, Peru. The deliverables of the research will enrich the current debate and discussions in relation to the use of such construction materials. The results will produce technical guidelines and a prototype that will not only help to more clearly understand the essence of potential use of cardboard in buildings but also allow the application of specific measures to reduce operating carbon dioxide emissions and consider the building regulations. The aim was achieved through the use of the EnergyPlus interface in DesignBuilder v7 to carry out a simulation study, in addition to the evaluation of three case studies and interviews with architects.

2. Context and Background Knowledge

The following section unveils the exploration of cardboard as a potential architectural construction material. An analysis is presented, spanning from its history to creation, production, and everyday applications, evaluating its properties. Additionally, it presents a history intertwined with technological advancements across generations and societal needs, seeking to reveal the hidden potential of an adaptable, eco-friendly, and versatile material that can make a significant contribution to the future of the construction industry. Furthermore, construction techniques and architectural typologies are examined.

Furthermore, the context of Lima, Peru, is analysed with topics related to geography, history, culture, socio-economic context, materials, and construction systems. These aspects will serve as the foundation for an investigation into the potential of cardboard as a construction material, aiming to venture into unexplored territories concerning sustainability and construction.

2.1. Paper/Cardboard: History and Applications

Paper, a widely used material, originated in the 2nd century AD [3], revolutionizing information storage and packaging across Asian, Arab, and European civilizations. Its introduction to architecture in the 8th century AD [1] marked a transition from heavy materials like stone to lighter alternatives [7]. Today, its properties—being lightweight, flexible, economical, and eco-friendly—make it a potential solution for sustainable construction, despite its declining prominence due to digital technologies [1,7].

Paper's invention, dated to 105 AD, evolved from natural processes observed in wasps [2]. During the Han Dynasty, it replaced bamboo and silk, using materials like bark and grass to create cellulose fibres via sifting, draining, and drying [8,9]. Similar materials included papyrus in Egypt, amate in Central America, and parchment in Europe, which were valued for their durability [3].

Cardboard's architectural use began in 8th-century Japan with techniques like shoji and fusuma [10]. By the 19th century, prefabricated cardboard houses emerged in France, while corrugated cardboard was patented in the U.S. in 1871 [11]. Industrialised paper production further expanded its applications.

The 20th century saw innovations like Stenman's newspaper summer house [1]. Architect Shigeru Ban advanced paper architecture in the 1980s, demonstrating the structural potential of paper tubes in projects like the 1995 "Paper House", the first permanent paper-based house approved in Japan [12]. His work, earning the 2014 Pritzker Prize, highlighted paper's strength, cost-efficiency, and adaptability. Other significant projects include cardboard classrooms by Cottrel and Vermeulen in the UK and Eekhout's designs at Delft University [1].

Paper production centres on cellulose from plants like bamboo and cane. The process involves creating pulp from logs through chemical and mechanical treatments, cleaning impurities, and forming fibres into sheets. These are pressed, dried, and coated before distribution, combining traditional methods with modern advancements [1].

2.1.1. The Material Properties

Cardboard, characterised by high density, can feature homogeneous or multi-layered reinforced structures. Its randomly orientated wood fibres measure 1–3 mm in length and 10–50 µm in width, with thickness ranging from 0.1 mm for paper to 0.3–0.4 mm for cardboard, and density of 0.5–0.75 g/cm^3 [10]. Density affects mechanical, physical, and electrical properties, including porosity, which allows air and liquid interaction [1,9]. Fibre alignment is primarily in the machine direction (MD), influencing structural performance [7].

Mechanically, cardboard properties are anisotropic, nonlinear, and hygroscopic, depending on fibre geometry, bonding, and additives. Wood cellulose fibres have an elastic modulus of ~35 GPa, with strength influenced by microfibril angle [13]. Its properties result from factors like fibre geometry, chemical composition, pulp type, additives, and production process, making it irregular, anisotropic, nonlinear, viscoelastic-plastic, and hygroscopic [14]. Thermal insulation is inherent, resembling that of wood, and is enhanced by corrugated or honeycomb designs trapping air. Sustainable uses include cellulose panels and heat-reflective cladding from recycled materials [7]. Acoustic insulation requires reinforcements or sandwich panels, with cellulose sprays improving absorption; tests show up to 38 dB separation [7].

Challenges include water resistance, as cellulose fibres weaken when wet, risking structural integrity. Moisture-resistant coatings improve performance but may reduce recyclability [7]. Fire resistance, vital in construction, is enhanced in thicker cardboard, which forms protective char layers. Recycled materials may include fire-retardant elements, achieving safety standards, though full structural fireproofing remains complex [7,15].

Fire resistance is a key factor to consider, as paper ignites at 230 °C. Thicker cardboard tubes improve fire resistance by creating char layers that act as a shield, much like wood. Moreover, recycled cardboard might contain residual ink with fire-retardant properties, contributing to adherence to fire safety standards [15]. Despite these advancements, balancing flammability, smoke, and toxicity remains crucial, with prototypes achieving 30 min fire ratings [7,15].

2.1.2. Cardboard in the Construction Industry

The construction industry's use of cardboard has been limited due to its perceived lack of reliability, with most applications focusing on recycled paper products from the packaging industry. However, paper tubes (used in architecture, notably by Shigeru Ban) are widely adopted for concrete formwork and other purposes. Manufactured through parallel or spiral winding, these tubes are vulnerable to moisture, which reduces their strength by 7–8% [16,17].

- Corrugated cardboard, primarily used in packaging since its invention in 1856, has mechanical properties that depend on the type and corrugation, with triple-wall boards offering significant resistance [1,18]. Though cardboard's use in foundations and floors/roofs is limited, projects such as Westborough Primary School and the Nemunoki Museum have demonstrated its potential despite challenges with moisture and material properties [7,19,20].
- Cardboard beams, columns, and panels face issues like buckling and require reinforcement, but they remain promising for temporary or single-story structures [1]. Connections in cardboard structures are typically made using high-strength adhesives or large bolts [7].
- Cardboard is an affordable, recyclable material with low embodied energy, although transport and reinforcement costs may increase its overall expense [7]. While security concerns persist, solutions like wire mesh and multi-layered designs can improve its safety and insulation properties [7,21].

2.1.3. Design Parameters

Cardboard reveals limitations in its application and design parameters, including stability, construction sequence, and load deflection (Table 1) [1].

Table 1. Design parameters (*Paper in Architecture* [1]).

Tensile/compressive strength: 8.1 N/mm
Long-term tensile/compressive strength taking into account the effects of creep deformation: 0.8–2.2 N/mm^2
E value (stiffness): 1000–1500 N/mm^2
The following values could be used for design 200 thick honeycomb sheets
Flexural strength: 6.9 N/mm^2
Design tensile/compressive strength taking into account the effects of creep deformation: 0.6 N/mm^2
E value (stiffness): 1000 N/mm^2

Origami, a traditional Japanese art form that involves paper folding to create various shapes, has inspired innovative approaches in architecture (Figure 1). The folding techniques in origami, known for their complexity and structural reliability, have potential applications in architecture, offering benefits like strength, efficiency, adaptability, and dynamism. Two notable folding patterns derived from origami are the Yoshimura Pattern and the Miura Ori Pattern [22,23].

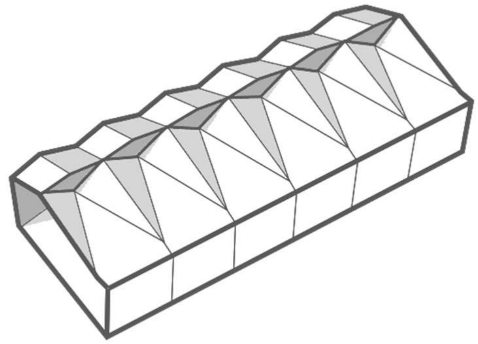


Figure 1. Origami design in architecture—Westborough primary school cardboard build (Authors).

The Yoshimura Pattern (Diamond Technique) is named after a Japanese scientist who observed this pattern in thin cylinders under axial pressure. It involves folding diagonals as valley folds and edges as mountain folds, forming a cylindrical shape. The pattern's curvature is influenced by the shape of the diamonds, which can be adjusted to create various continuous curves like segments of circles or parabolas (Figure 2) [23,24].

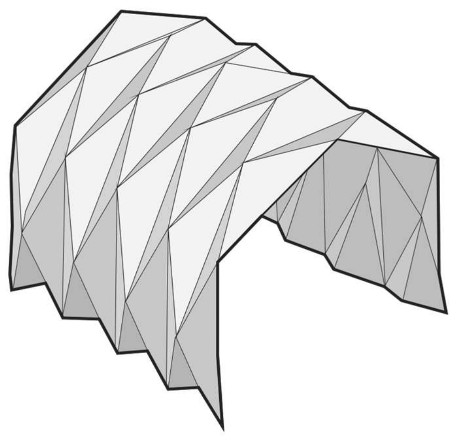


Figure 2. Yoshimura folding technique (Authors).

The Miura Ori Pattern (Fishbone Pattern) involves repeating reverse folds to create a zigzag shape that can expand and contract in both directions. The pattern consists of equal trapezoids generating a fishbone-shaped tessellation. The zigzag line's curvature is determined by the inclination of the trapezoid legs, allowing for different structural forms depending on the angles used (Figure 3) [22].

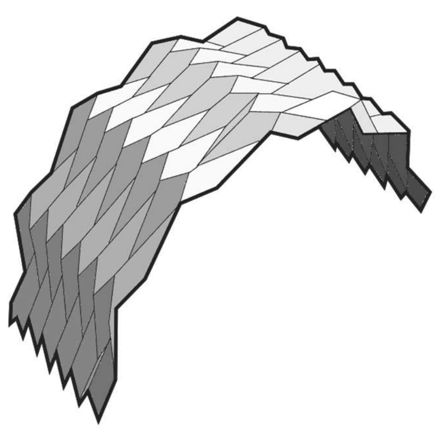


Figure 3. Miura Ori folding technique (Authors).

It was necessary to deepen knowledge related to the application of cardboard as a construction material in the construction industry at a global level. Topics were introduced on the history of the material, production processes, properties, relationships with architecture and construction, and concepts and techniques as design strategies. Various investigations highlighted the good insulating and sustainable properties of cardboard as a construction material.

2.2. Lima

Lima, known as the "City of Kings", was founded in 1535 and became the epicentre of Spanish rule in South America. Located on the Pacific Ocean, it is one of the largest and most populous cities in Latin America, serving as Peru's industrial, economic, political, and commercial hub [4]. Renowned for its cultural diversity and culinary heritage, Lima has been recognised as the "Best Culinary Destination in Latin America" [25]. Its cultural identity reflects pre-Hispanic, colonial, Western, and Eastern influences, evident in its cuisine and historic architecture. However, the city faces challenges such as informality, with a 73.9% informal employment rate [6], along with socio-political instability and corruption [5].

The preservation of Lima's architectural heritage, including its historic centre, is threatened by urban pressures [26,27]. Despite these challenges, the city offers diverse attractions, ranging from its culinary delights to its cultural and commercial opportunities [28].

Lima is central to this study due to its political, economic, and social significance, attracting major construction investments. While its high humidity and seismic risks pose challenges, its temperate climate supports experimentation with alternative building materials like cardboard. Cardboard is affordable, recyclable, and aligned with the city's growing environmental awareness, making Lima a promising location for sustainable and innovative construction practices.

2.2.1. Lima's Climate

Lima's climate is influenced by the Humboldt Current, characterised by a desert and subtropical climate with nearly 100% humidity and persistent fog [29]. It is one of the driest cities globally, with average temperatures ranging from 17 °C to 22.5 °C. However, during the "El Niño" phenomenon, temperatures rise, often causing severe flooding [30]. Poor urban planning exacerbates the economic impact of such natural events, particularly in vulnerable areas. Constant exposure to the marine environment necessitates corrosion-resistant materials and durable construction techniques.

Lima, classified as primarily dry with a hot desert climate (BWh) in urban areas, cold desert climates (BWk) in rural highlands, cold semi-arid climates (BSk), and tundra (ET) under the Köppen–Geiger system [31], suffers from chronic water shortages (Figure 4). Despite its coastal location, desert conditions, poor urban planning, water contamination, and phenomena like "El Niño" contribute to these issues. Ten percent of the population lacks access to public water networks, and 23% are without sewage systems [32].

Seismic risks are heightened due to Lima's location on the "Pacific Ring of Fire", where tectonic plates converge [33]. Informal construction and poor urban planning further increase vulnerabilities. Green space is also limited, with only 3.1 m^2 per inhabitant compared to the WHO's recommended 9 m^2, exacerbating pollution and reducing urban habitability [34].

Population growth has strained urban infrastructure, including transportation. The city's public transit system, comprising a 21.48 km metro line, Metropolitan buses, and traditional transport options, is inadequate due to chaotic traffic and poor planning. Recent efforts, such as expanding bike lanes, aim to promote sustainable mobility, though congestion and pollution persist [35].

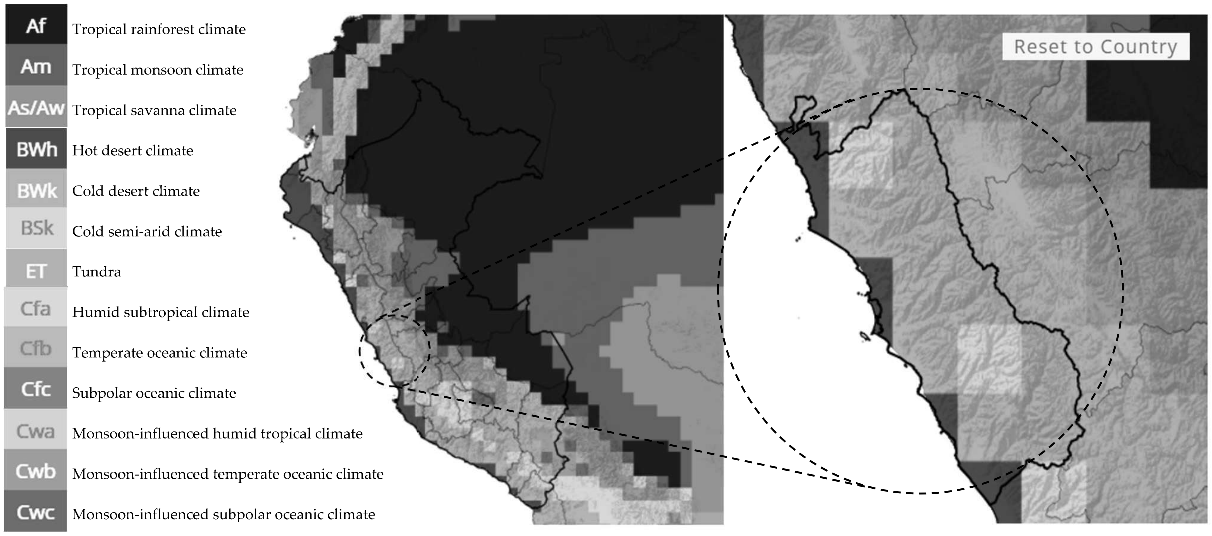


Figure 4. Peru and Lima DfB climatic zone—the Köppen–Geiger classification (Source: CCKP, 2024 [31]).

2.2.2. Construction Practices

Construction methods in Peru have evolved based on material availability, technological advancements, and socioeconomic factors. During the pre-Inca era, cultures like the Moche and Nazca used adobe for complex structures, while the Inca Empire (1438–1533 A.D.) specialised in stone construction for iconic sites like Machu Picchu [36,37].

Colonial architecture introduced by the Spanish included materials such as bricks, tiles, adobe, stone, and wood, featuring Renaissance, Mudejar, and Baroque styles [26]. By the 19th century, trends like Neoclassicism and Eclecticism became prominent until Peru's independence in 1821 [26].

In the early 20th century, reinforced concrete enabled multi-story buildings, with architectural styles such as Neoclassicism and Art Deco dominating [27,38]. By the mid-century, functional designs using reinforced concrete gained popularity, influenced by Le Corbusier's principles and emphasising seismic-resistant regulations. Notable examples include the University City of the National University of San Marcos in Lima [27].

The 1960s and 1970s saw the rise of Brutalism, exemplified by the Civic Centre and the PetroPerú building [39]. Since the 1980s, contemporary architecture has embraced diverse styles, integrating modern technologies, prefabrication, and sustainable practices, alongside Building Information Modelling (BIM) for greater efficiency [27,38–40].

2.2.3. The Unresolved Issues in Lima

The paper industry in Peru is underdeveloped, with per capita consumption at only 12 kg compared to 50 kg in other countries, meeting just 35% of national demand [41]. Companies like "Industrias de Papel" and "Trupal" operate in Lima, offering recycling services, but only 1.9% of waste is recycled nationwide [42]. Implementing advanced recycling processes could enhance the use of paper and cardboard in construction.

Lima's geographic conditions, including humidity and seismic activity, limit cardboard's application in construction. Additionally, high rates of informal housing (80% of homes) and non-compliance with regulatory standards complicate efforts to introduce innovative materials [43].

Despite these challenges, cardboard offers economic and environmental advantages, particularly in low-resource areas. The Sustainable Construction Technical Code (Supreme Decree No. 014-2021) promotes ecological strategies, but research and experimentation with cardboard in construction remain limited [44]. International studies provide a foundation for its potential adoption in Peru.

Lima's history of adaptive construction practices underscores its potential for sustainable innovation. Its role as Peru's political and economic centre, coupled with its favourable climate for experimentation, makes it an ideal location for developing eco-friendly construction methods using cardboard. While challenges persist, including limited recycling infrastructure and societal resistance, Lima presents significant opportunities for advancing sustainable practices.

3. Methodology

The methodologies that were implemented in the investigation of cardboard as a construction material were essential to developing a set of guidelines. This research combines qualitative and quantitative methods, incorporating case studies of existing projects, interviews with architects and engineers from diverse backgrounds, online questionnaires, and the simulation of an existing school building.

Ethical approval was secured from the research ethics committee of De Montfort University, ensuring adherence to ethical principles and the integrity of the research endeavour that protects the rights and well-being of participants.

The work focuses specifically on architecture related to cardboard as a sustainable material, exploring its potential to be introduced into the construction industry in the specific environment of Lima, Peru.

There are certain limitations in this article, emphasising that Peru is at an early stage in terms of the development of sustainable practices. For this reason, no case studies have been found in this context or in the region, which is why case studies are taken from other countries that are related in terms of climatic, geographical, etc., characteristics. Additionally, the interviews and surveys are limited to obtaining points of view from architects with experience in the subject who live in England, the Netherlands, and Peru. Finally, it should be noted that the results provided by the DesignBuilder software are approximations and not 100% accurate data.

3.1. Methodological Flowchart

The research methodology is visually represented in a flowchart that describes the process and components involved in the study. It is based on secondary data analysis, including a thorough literature review and a contextual study. Based on this research, a research gap was identified, which served as a basis for formulating research questions and objectives. To address these objectives, primary data were collected through qualitative methods, such as interviews and case studies, complemented by quantitative approaches, such as surveys and simulations. The aforementioned quantitative methods were implemented after the qualitative ones to address all comments, aspects, and questions in this phase.

The analysis of this primary data led to the development of findings and limitations, which were essential for creating a set of guidelines and prototyping a cardboard building (Figure 5). These methodologies aimed to deepen the understanding of cardboard as a building material and contribute to the development of a comprehensive sustainable building design.

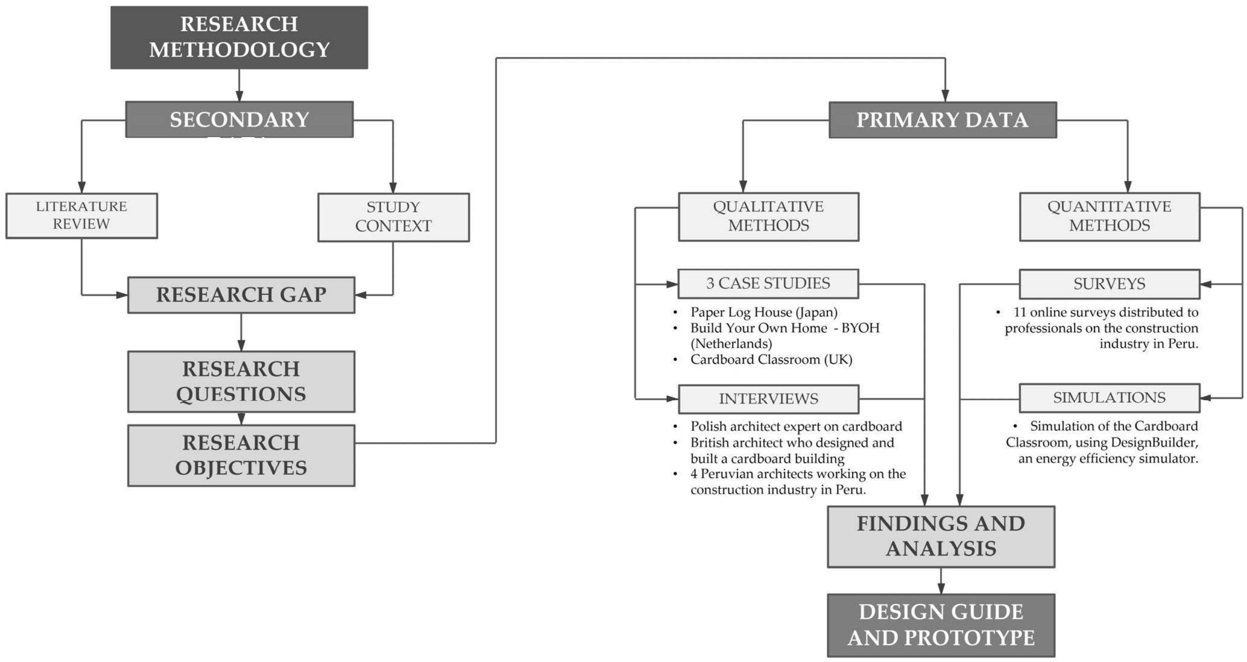


Figure 5. Methodology flowchart (Authors).

3.2. Case Studies

Three architectural projects made from cardboard were analysed to gather crucial data for the development of a set of guidelines. These projects highlight the versatility and potential of cardboard as a sustainable building material, which is used as the main material in all three case studies, both for the structures and for the enclosures and finishes:

- Paper Log House (Japan): Developed by Shigeru Ban for humanitarian purposes, this emergency shelter offers fast, low-cost housing solutions for disaster victims. It uses local, inexpensive, and recycled materials and can be quickly assembled, demonstrating the potential of cardboard for emergency construction. Cardboard predominates throughout the building, from the foundations to the walls and roof.
- BYOH Prototype (Netherlands): Part of a competition at Delft University supervised by Jerzy Latka, this project involves a rapid deployment shelter that can be erected in five minutes using origami folding techniques. This prototype explores the use of cardboard in temporary and adaptable structures.
- Cardboard Classroom (UK): an educational space in Southend-on-Sea, UK, designed by Cottrell and Vermeulen Architecture with Buro Happold Engineering in 2001. It is known for being Europe's first cardboard structure, initially intended to last 20 years but still in use today. The project aimed to minimise the environmental impact of construction by using sustainable materials such as paper and cardboard for a permanent structure. Cardboard is used for much of the building, except for the foundation and some structural joints.

The criteria for these three case studies are based on their use of cardboard as a sustainable building material. Paper Log House (Japan) and Cardboard Classroom (UK) use locally recycled materials, while the BYOH Prototype (Netherlands) utilises origami folding techniques for quick assembly. These projects highlight cardboard's adaptability, cost efficiency, and ease of construction for both temporary and permanent structures.

Although there are no direct case studies in Peru, these examples are relevant to Lima's needs, offering solutions for housing, education, and disaster management. Lima faces challenges like rapid urban growth, high poverty, and vulnerability to natural disasters, making cardboard construction a viable, sustainable alternative for emergency situations and resource-limited contexts. Furthermore, cardboard's insulating properties could benefit Lima's hot, humid climate.

3.3. Interviews

The research methodology included personal video call interviews targeting architects, engineers, and individuals knowledgeable about cardboard as a construction material. In-depth interviews were conducted with one architect from each of Britain and Poland and four Peruvian architects to gain insights based on their experiences. Participants, who must be of legal age, provided informed consent and were assured of confidentiality and data security. The interviews were conversational, allowing participants to freely express their views while providing necessary information.

3.4. Surveys

Twelve online surveys targeted architects, engineers, and individuals knowledgeable about cardboard as a construction material. These were distributed online, adhering to security protocols to protect participants' integrity. The questionnaires aimed to collect data quickly and efficiently from a global audience. They consisted of semi-structured questions to gather clear and concise responses. Participants had varying levels of knowledge about cardboard in construction, and questions addressed perceptions of cardboard's role in building design, as well as comfort and functionality in cardboard structures.

The focus of both interviews and questionnaires was on participants' perceptions of cardboard as a construction material, comfort levels in cardboard buildings, and the feasibility of sustainable cardboard projects. Specific questions were tailored to professionals who had worked with paper projects to gather data for the future toolkit.

3.5. Simulations

The research utilised the DesignBuilder software v7 for simulation, focusing on an existing school building in the UK to analyse energy performance. This involved modelling the architectural project and conducting simulations to assess energy use, thermal comfort, lighting, ventilation, temperature, solar paths, and overall energy efficiency. The simulations provide a comprehensive understanding of the advantages and disadvantages of cardboard buildings and enable the adoption of strategies to improve energy performance.

4. Case Studies

This paper analyses four significant case studies to explore the feasibility of cardboard as a viable construction material for future commercial applications. These projects serve as icons and precedents, illustrating cardboard's potential as a sustainable and reliable construction material. The primary goal of this analysis is to gather essential information through qualitative research that will aid in the development of a set of guidelines for cardboard as a construction material in the future.

Several limitations are inherent in this research approach. The analysis focuses on specific parameters of each project but does not consider the experiences of the occupants. To address this gap, complementary methodologies such as interviews, questionnaires, and simulations were employed to capture occupant experiences in cardboard buildings. Another limitation is the scarcity of paper architectural projects in Peru and its surroundings, necessitating the inclusion of reference projects from Japan, the Netherlands, and the United Kingdom.

4.1. Case Study I: Paper Log House (Japan)

The Paper Log House, designed by Shigeru Ban in 1995, is a landmark project that exemplifies his commitment to humanitarian architecture. The project was initiated through the Volunteer Architects Network (VAN), a non-governmental foundation dedicated to creating efficient and temporary shelters for victims of natural or man-made disasters. This initiative focused on three major earthquakes: Kobe, Japan (1995), Kaynasli, Turkey (1999), and Bhuj, India (2001), which left many people homeless [1].

Design System, Structure, and Energy Efficiency: The first prototype was developed in Kobe, Japan, featuring a simple yet effective design for 27 houses, each measuring 4×4 m. The walls were constructed from paper tubes with a diameter of 108 mm and a thickness of 4 mm, assembled using self-adhesive, waterproof foam tape. Horizontal steel rods added structural support, and the tubes were anchored with wooden pegs. A creative foundation solution involved using beer crates filled with sandbags for added stability. The roof was made from a PVC tent membrane, allowing for natural ventilation and thermal control. The entire structure was coated with a polyurethane-based varnish to improve thermal efficiency [1,12].

Design Team and Execution: The project was a collaborative effort involving Ban's students and architects from around the world. The construction process was straightforward, requiring only a foreman and ten volunteers to assemble each house in approximately six hours. The project was notable for its low cost (approximately USD 2000 per house), ease of assembly and disassembly, and the camaraderie it fostered among participants. Although the general design remained consistent, each Paper Log House project was adapted to local materials, cultural context, and environmental conditions [12].

4.2. Case Study II: Build Your Own Home—BYOH (Netherlands)

In 2015, the Faculty of Architecture at Delft University of Technology hosted a design competition focusing on paper as a construction material, resulting in the BYOH (Build Your Own Home) project. This project aimed to create a sustainable, rapidly deployable shelter using origami techniques, specifically the Miura and Yoshimura Patterns. The project was led by students Chris Borg Costanzi, Andrius Serapinas, Antonia Kalatha, and Dorine van der Linden, under the guidance of Jerzy Latka and Marcel Bilow [1].

The BYOH shelter was designed for quick and efficient deployment, leveraging the Miura Fold and Yoshimura Pattern to create a foldable, hemispherical structure with an arched entrance. The final structure measured 1.85 m in height, 3.90 m in width, and 4.20 m in length, consisting of triangular and rhomboidal panels made from three layers of cardboard, providing thermal insulation and structural stability [1].

The shelter combined both origami patterns, with the Yoshimura Pattern forming the main body and the Miura Pattern shaping the entrance. The structure was supported by an arch made from corrugated cardboard layers, reinforced with wooden plates and elastic cords. The floor was constructed from plywood with a honeycomb layer for added stability [1].

A significant challenge in the BYOH project was the development of connections due to the thin origami sheets. This led to the creation of "living hinges"—laser-cut lines that enhanced the cardboard's flexibility. Transparent adhesive tape reinforced with fibres was used to join the cardboard panels. The project culminated in a 1:2 scale prototype, demonstrating the potential for creating larger complexes by connecting multiple BYOH units. The project was recognised for its practicality and innovative use of origami in emergency housing solutions [1].

4.3. Cardboard Classroom (UK)

The school, located in Southend-on-Sea, UK, was designed by Cottrell and Vermeulen Architecture in collaboration with Buro Happold Engineering in 2001. This 90 m^2 educational space was Europe's first cardboard structure, intended for a 20-year lifespan, though it remains operational today. The project aimed to minimise the environmental impact of construction materials by using sustainable materials such as paper and cardboard [12].

The classroom features two interior walls made of 11 paper tubes each, supporting a wooden roof (Figure 6). Seven additional paper tubes are located near the sliding glass doors, which provide ventilation and natural light. The walls and roof are composed of cardboard and honeycomb panels, reinforced with polyethylene on the interior and waterproof paper on the exterior. An outer layer of fibre-cement enhances thermal insulation. Vapour chambers were incorporated to reduce moisture, and fire-resistant treatments were applied. The connection between walls and the roof was achieved with prefabricated wooden components and screws anchored to a wooden frame [12].

a. Seven paper tube columns and wooden beam, roof made from cardboard and honeycomb panels
b. Front façade- walls and roof from cardboard and honeycomb panels
c. Truss for skylight windows
d. Structural wall made from 11 paper tube columns and a steel
e. Wooden truss for skylight windows, walls and roof from cardboard panels

Figure 6. Photos taken on site (Authors). Image 7.6.1.5—Cardboard Classroom front facade (Authors).

The structure underwent various tests for envelope optimisation, water and fire resistance, creep, and durability (Figure 7). Despite initial successes, issues such as cardboard deformation emerged four months post-construction, necessitating repairs to the support tubes. Buro Happold identified the paper's sensitivity to atmospheric moisture and recommended a waterproof barrier. Flexural and compression tests revealed the material's limitations, with tube creep beginning at 10% of the maximum compression level and the need to limit long-term loads to 1.6 MPa. Larger-diameter tubes were found to be weaker due to the winding angle during production. Additionally, the roof required complete replacement years later due to weather damage [1].

Damp and deterioration evidence in walls and structure

Ceiling and structure

Connection between paper tube column and wood truss

Back façade—sliding wood and glass doors that provide ventilation and lightning

Figure 7. Photos taken on site (Authors). Image 7.6.1.9—Cardboard Classroom—back facade (Authors).

While the project was initially a research prototype, the costs were reduced through mass production of materials. Acoustic insulation was not a requirement, but the material provided a noise insulation level of 38 dB. The project faced challenges with construction permits and approvals, highlighting the scepticism and lack of confidence in paper as a construction material [1].

The study visits in 2022–2024 aimed to gather first-hand experience and form a personal judgement on the case study. Before each visit, relevant questions were prepared for the school staff (Figures 3 and 4). During the visits, graphical information was collected, and every detail was observed. The internal spaces were found to be comfortable, with a warm temperature inside despite the autumn cold and adequate lighting provided by large sliding glass doors, circular windows, and skylights. Some moisture was observed in wall corners and on the lower ends of paper columns, along with minor deterioration of finishes, likely due to a lack of maintenance. Despite these issues, the building has remained efficient for over 20 years. The origami-inspired zigzag and diagonal forms contributed to a sense of solidity and structural security. Overall, the visits to the Cardboard Classroom were highly satisfying and reinforced the belief that cardboard can be a viable, sustainable option for constructing permanent buildings.

The first cardboard building constructed in Europe was designed with a projected lifespan of 20 years, yet it remains fully operational today. However, several challenges and issues have arisen over time. One major issue is the sensitivity of paper to moisture, which led to the deformation of the cardboard structure and the replacement of some cardboard columns, affecting the building's structural integrity (Figure 4). Additionally, the roof had to be entirely replaced due to weather damage. These problems highlighted the need to reinforce cardboard panels with a waterproof layer. Despite facing challenges related to construction permits, largely due to scepticism about paper as a viable construction material, the project ultimately demonstrated significant cost reductions. Although the initial costs were relatively high, the final expenses were considerably lower due to mass production, recycling, and the low relative cost of paper.

These case studies highlight the versatility and potential of paper as a construction material, particularly in the context of emergency shelters. Shigeru Ban's Paper Log House showcases the importance of using local, recyclable materials and simple construction methods to create dignified, efficient shelters. The BYOH project exemplifies how innovative design techniques, such as origami folding, can lead to rapid, sustainable shelter deployment. Both projects underscore the importance of context-specific adaptations and provide valuable insights for future research in sustainable design and construction. Moving forward, methods such as interviews and questionnaires were employed to gather further data on these innovative approaches.

5. Interviews and Questionnaires

Data were collected from participants through interviews and questionnaires with the goal of understanding individuals' personal perspectives regarding their experiences with cardboard construction projects. This research utilises two types of interviews: on the one hand, interviews with an English architect and a Polish architect, specifically related to the projects exposed in the case studies in Japan, the Netherlands, and the United Kingdom, to obtain direct insights into the design and construction processes, motivations, challenges, and material properties of cardboard. On the other hand, interviews with architects based in Lima, Peru, to assess their knowledge and perceptions of cardboard in the construction industry. The objective was to facilitate a conversational approach to extract nuanced experiences and viewpoints from each participant.

For surveys, semi-structured and anonymous questionnaires were designed to gather precise and targeted responses, similar to the interview questions. The participants were Lima residents, providing insight into the perception of cardboard as a construction material within the city.

The findings aim to contribute to the architectural design toolkit, promoting cardboard as a viable construction material to enhance users' quality of life.

This study acknowledges limitations, particularly the greater manageability of surveys compared to interviews, due to constraints such as participant availability and willingness. Consequently, the number of interviewees is more limited compared to survey respondents.

5.1. Interview Results and Findings

Interviews were conducted with a total of six architects, including two with extensive experience in cardboard construction: an English architect (participant 1), a Polish architect (participant 2), and four architects from Lima (participants 3, 4, 5, 6). Below are the questions asked in the interviews, accompanied by the most relevant key answers that are considered to contribute to the development of the set of guidelines. It is worth mentioning that both participants 1 and 2 were asked some specific questions:

Q1: What motivated you to explore paper as an object of study?

Q2: Why do you think the material is not common in the construction industry? What are the gaps or unresolved problems?

Q3: What were the biggest challenges in developing the Cardboard Classroom project? How difficult was it to deal with local authorities and regulations?

Q4: Would it be feasible to build paper buildings taller than 1 story? Would it be viable to build paper buildings with a life cycle of more than 20 years?

Q5: If you had to develop a guide manual on the design of projects on paper or cardboard, what general ideas would you propose?

Q6 only participant 2: Regarding the development of the thesis "Paper in Architecture", what general conclusions, general learnings did the thesis leave you? How much has your interest and perception changed with respect to the material applied to the field of architecture and construction today?

Q7 only participant 2: What is your opinion about the BYOH project? Comments on the concept of origami, the efficiency of applying these techniques, and if you see a future for future applications.

The insights gathered from the participants revealed key considerations regarding the use of cardboard and paper as construction materials. Participant 1 emphasised the sustainability and recyclability of cardboard, noting its potential for use in furniture and doors. However, significant challenges, such as structural connections, susceptibility to humidity, and fire risk, limit its application. Currently, cardboard is not viable for multi-story buildings unless used in hybrid structures.

Participant 2 highlighted the appeal of paper as a blend of traditional and innovative materials but noted that it will not replace conventional materials. The limited use of paper in construction was attributed to the lack of standardisation, global recognition, and public trust. Additionally, origami was suggested as an architectural solution, particularly for thin materials. Participant 2 also asserted that current fire regulations prevent the construction of multi-story cardboard buildings, though he was open to the possibility with further research. He suggested a set of guidelines focusing on using sustainable materials and reducing concrete use.

The interviews with participants from Lima revealed a general lack of knowledge and confidence in using paper for construction, though they recognised its potential for interior design, furniture, and temporary structures. The low popularity of paper is linked to limited knowledge and a lack of governmental initiatives, although private companies are beginning to implement sustainable practices. Key limitations identified include high humidity, earthquakes, societal conservatism, informality, and political and economic instability. All participants agreed that constructing multi-story cardboard buildings is currently unfeasible, but they remained open to exploring its potential with more research and information.

5.2. Questionnaire Results and Findings

A survey was carried out with eight questions, corresponding to the perception of cardboard as a construction material. The selected participants were professionals who reside in Lima and who have knowledge of the construction industry. A total of 11 participants answered the questionnaire.

Q1: How familiar are you with the use of cardboard as a construction material in architecture projects? (Figure 8)

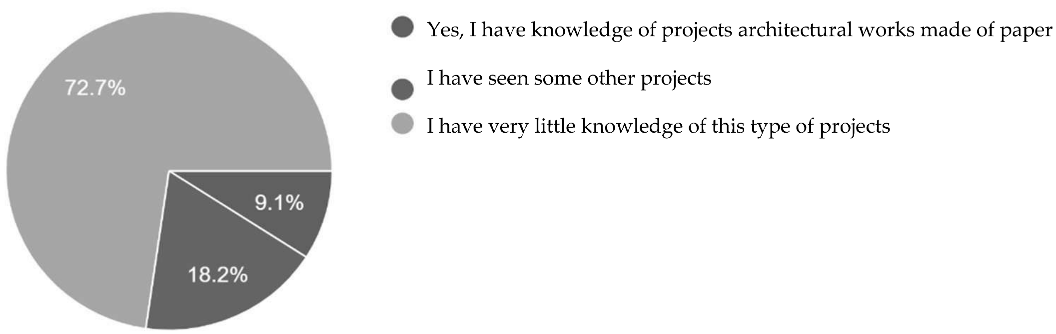


Figure 8. Online questionnaire result chart (Source: Authors via Google Forms).

Q2: What is your perception regarding paper as a construction material? What advantages and disadvantages could you identify in its implementation?

Q3: On a scale of 1 to 10, how reliable or unreliable do you see cardboard as a component (architectural and/or structural) of building construction? (Figure 9)

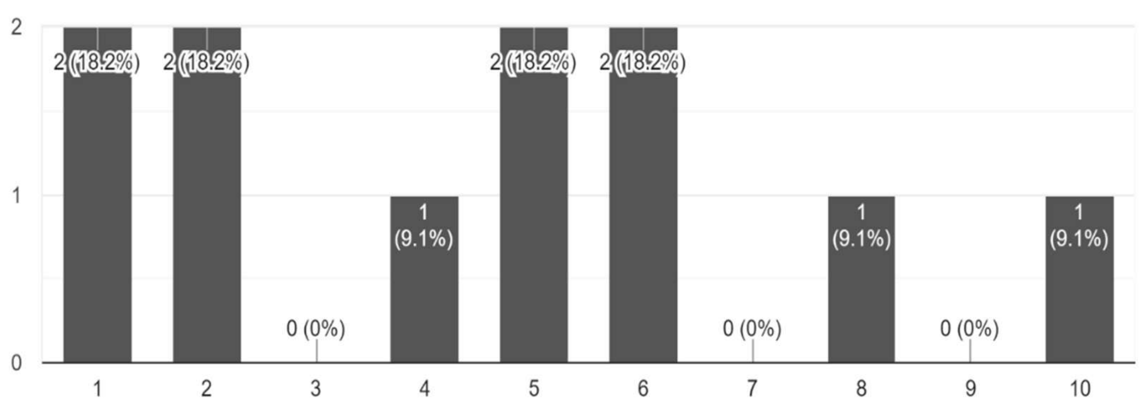


Figure 9. Online questionnaire result chart (Source: Authors via Google Forms).

Q4: Are there policies, regulations or incentives from the government and/or local authorities related to the development of sustainable strategies and constructions in Peru? (Figure 10)

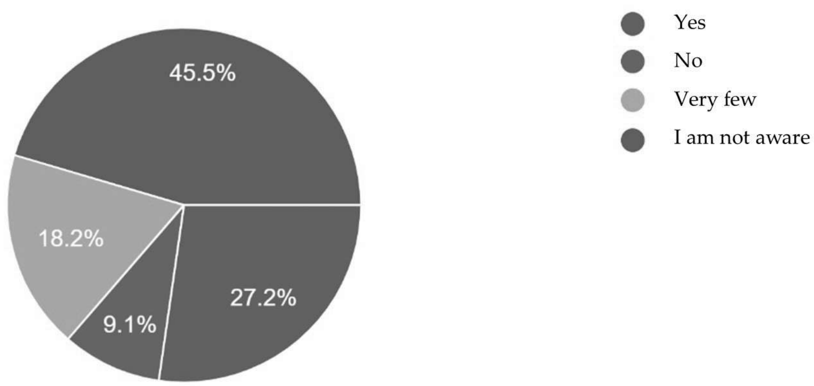


Figure 10. Online questionnaire result chart (Source: Authors via Google Forms).

Q5: How much interest is there from authorities, professionals in the design and construction sector and from citizens in promoting and taking action on environmental initiatives? For example, lower energy consumption, reducing CO_2 emissions, recycling, sustainable transport, etc. (Figure 11)

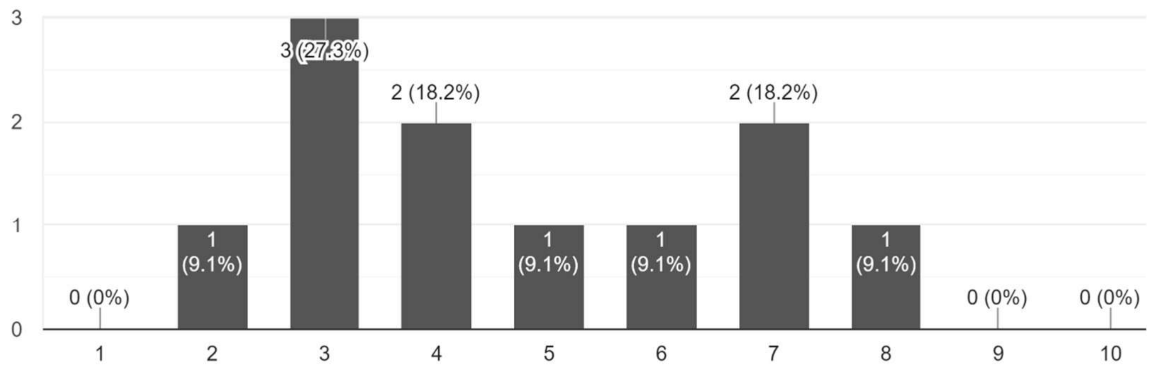


Figure 11. Online questionnaire result chart (Source: Authors via Google Forms).

Q6: How do you view the option of incorporating paper-based materials in construction as an alternative to traditional materials and methods? Do you think this material can replace them? Or perhaps be a secondary complement or alternative? (Figure 12)

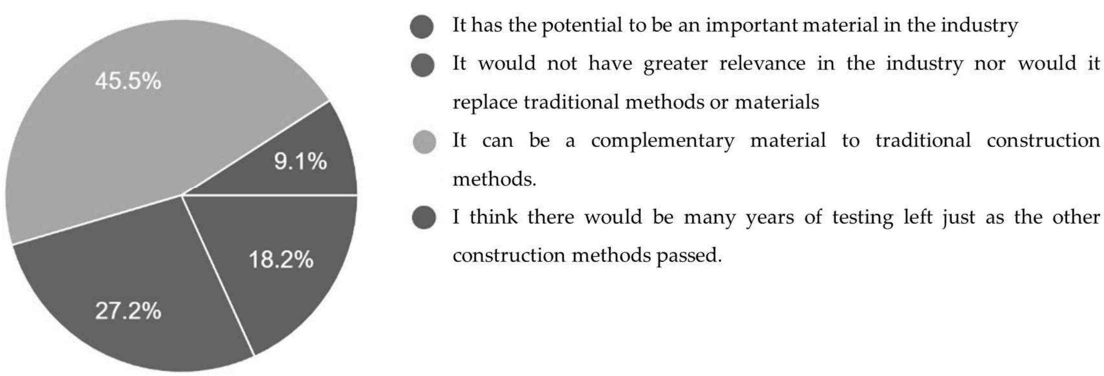


Figure 12. Online questionnaire result chart (Source: Authors via Google Forms).

Q7: How satisfactory do you see paper/cardboard with respect to user comfort and safety? (Figure 13)

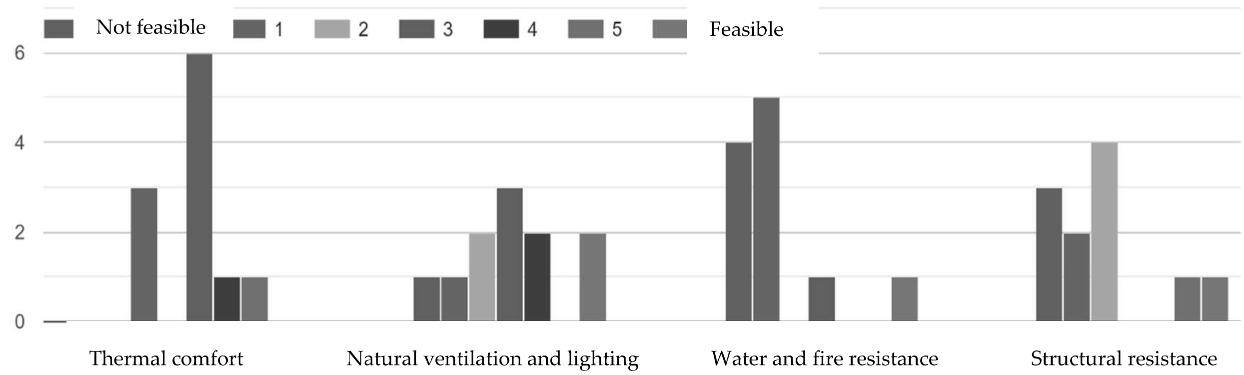


Figure 13. Online questionnaire result chart (Source: Authors via Google Forms).

Q8: Do you think it is feasible to develop architectural projects made of paper as the main material (corrugated cardboard panels, paper tubes, etc.) in a city like Lima? (Figure 14)

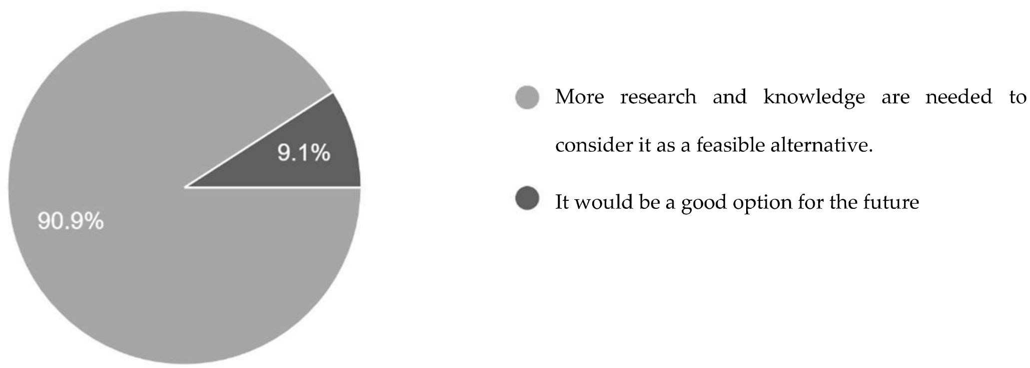


Figure 14. Online questionnaire result chart (Source: Authors via Google Forms).

Knowledge and Perception: 72.7% of respondents indicated limited knowledge of cardboard as a construction material, reflecting the findings about the low interest in sustainable strategies in Peru (Figure 8).

Advantages and Disadvantages: Cardboard is perceived ambiguously, with some recognising its sustainability, cost-effectiveness, and potential for temporary projects, while others view it as fragile and unreliable. Concerns about durability, water resistance, and limited knowledge are prevalent.

Reliability: The perception of cardboard as a reliable architectural component is mixed, with 36.4% finding it unreliable, 36.4% neutral, and a minority seeing potential (Figure 9).

Regulations and Interest: Awareness of sustainable design regulations is low, with 45.5% being unaware, highlighting the need for increased governmental focus on eco-environmental policies. The private sector is noted for promoting sustainable actions, but broader societal awareness requires further efforts (Figure 10).

Future Prospects: The majority (45.5%) view cardboard as a complementary material rather than a primary industry player. While 27.2% see no future for cardboard, 18.2% express optimism for its potential in Lima, contingent on further research (Figure 12).

Challenges and Opportunities: Cardboard's thermal performance is seen as average, though superior to that of traditional materials like brick. Water and fire pose significant challenges, with 60% agreeing on these issues. Structural confidence remains low, but a minority recognise cardboard's potential (Figure 13).

Research Gap: An overwhelming 90.9% believe there is a significant gap in knowledge and research on cardboard, with only 9.1% viewing it as a future option for construction in Lima (Figure 14).

Paper is more seen as a complementary material in buildings that typically have one or two floors.

Lastly, the participants state that they are in favour of research, testing, and experimentation, with the aim of being able to see an innovative material, such as cardboard, introduced to the world of architecture.

6. Dynamic Thermal Simulation

Building simulations were developed to assess the energy efficiency of a building constructed with cardboard. DesignBuilder software v7 was utilised to evaluate the Cardboard Classroom project at Westborough Primary School in Westcliff-on-Sea, UK, which was previously presented and analysed in Section 4.3. The methodology began by modelling the case study and inputting contextual data, such as location, materials, lighting, and ventilation, into the software. This process aimed to determine the building's comfort and sustainability, identify areas for improvement, and contribute to a set of guidelines for future applications.

6.1. DesignBuilder Modelling

The initial step in the methodology involved modelling the reference project using comprehensive data to create accurate 2D and 3D models (Figures 15–17). The location and internal space characteristics are crucial for precise climatological analysis and simulations.

Comparing the U-values of the walls, roof, and floor of the cardboard building with the values of the Building Regulations 2010 [45] shows they do not comply with current standards. However, the building is more than 20 years old and complied with sustainable standards of the time, and the building consumes 11% less energy than one built with traditional materials (Table 2) [1].

Table 2. Cardboard Classroom data (Authors).

DesignBuilder version	Version 7.0—EnergyPlus 9.4	
Site location	MacDonald Ave, Westcliff-on-Sea, Southend-on-Sea, Westcliff-on-Sea SS0 9BS	
Longitude and latitude	51°32′50.0″ N 0°41′56.4″ E	
Orientation	Southeast	
Floor height	3.50 m	
Activity template	Educational	
Occupied floor area	90 m^2	
	Building Regulations standards [45]	**Westborough cardboard building**
Wall U-value	0.26 W/m^2K	0.32 W/m^2K
Roof U-value	0.16 W/m^2K	0.32 W/m^2K
Ground floor U-value	0.18 W/m^2K	0.39 W/m^2K

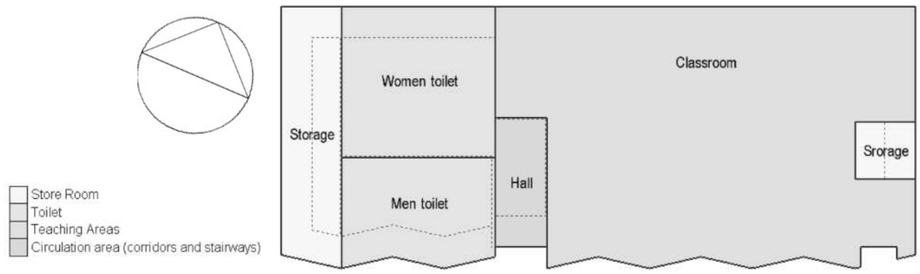


Figure 15. Cardboard Classroom floorplan (Authors via DesignBuilder). Image 7.4.1—Cardboard Classroom floorplan (Authors via DesignBuilder).

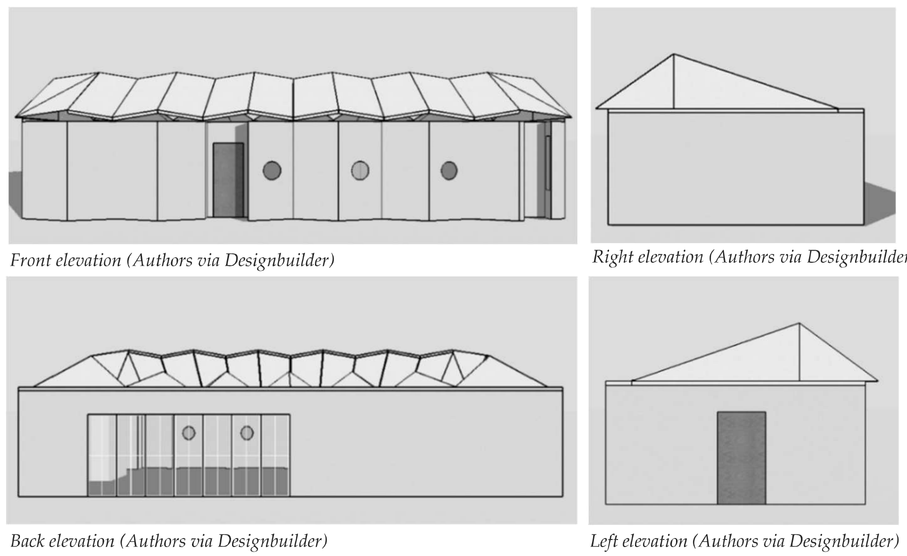


Figure 16. Elevations (Authors via DesignBuilder). Image 7.4.4—Back elevation (Authors via DesignBuilder).

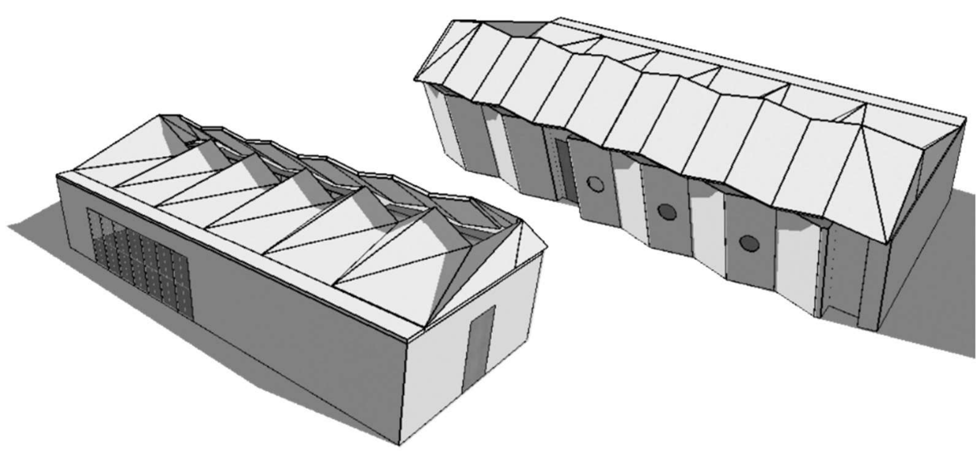


Figure 17. Cardboard Classroom (Authors via DesignBuilder). Image 7.4.1—Cardboard Classroom floorplan (Authors via DesignBuilder).

6.2. Sun Path Analysis

The study was conducted considering 4 months of the year (March, June, September, and December) and two different time periods (9:00 a.m. and 3:00/5:00 p.m.). The good orientation of the building is evident in a way that solar incidence is not overwhelming, taking into consideration that the building's purpose is a classroom, thus requiring controlled light entry. The facades that receive the light are the south and west, and these have precisely limited and controlled light entry to prevent excess light. Additionally, a unique design and treatment of the roof can be observed, which provides the classroom with both zenith light and natural ventilation (Figure 18).

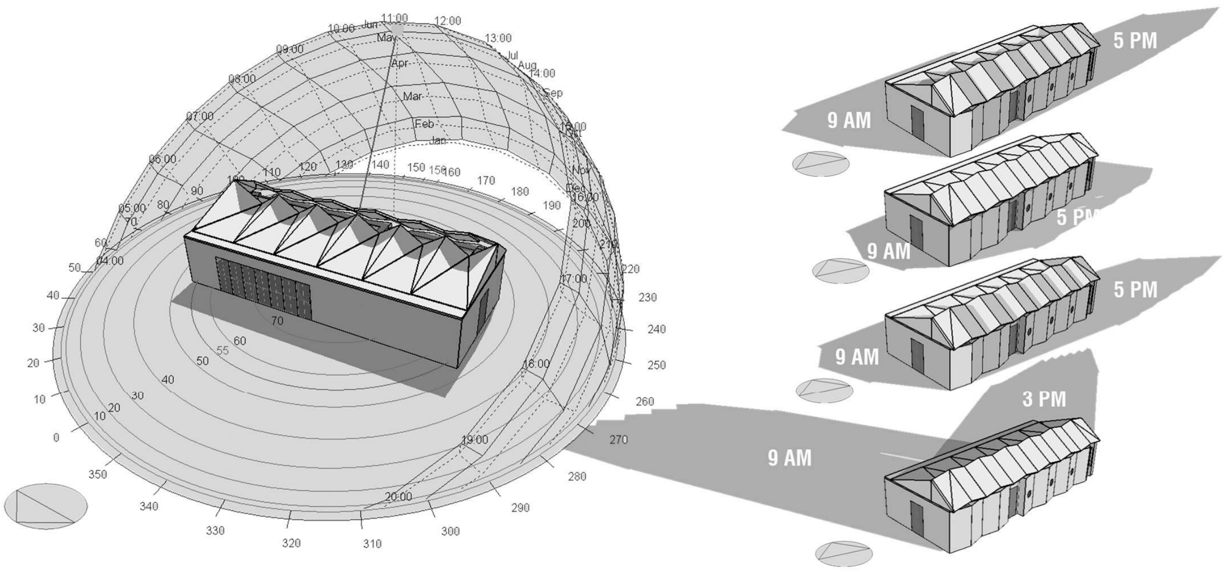


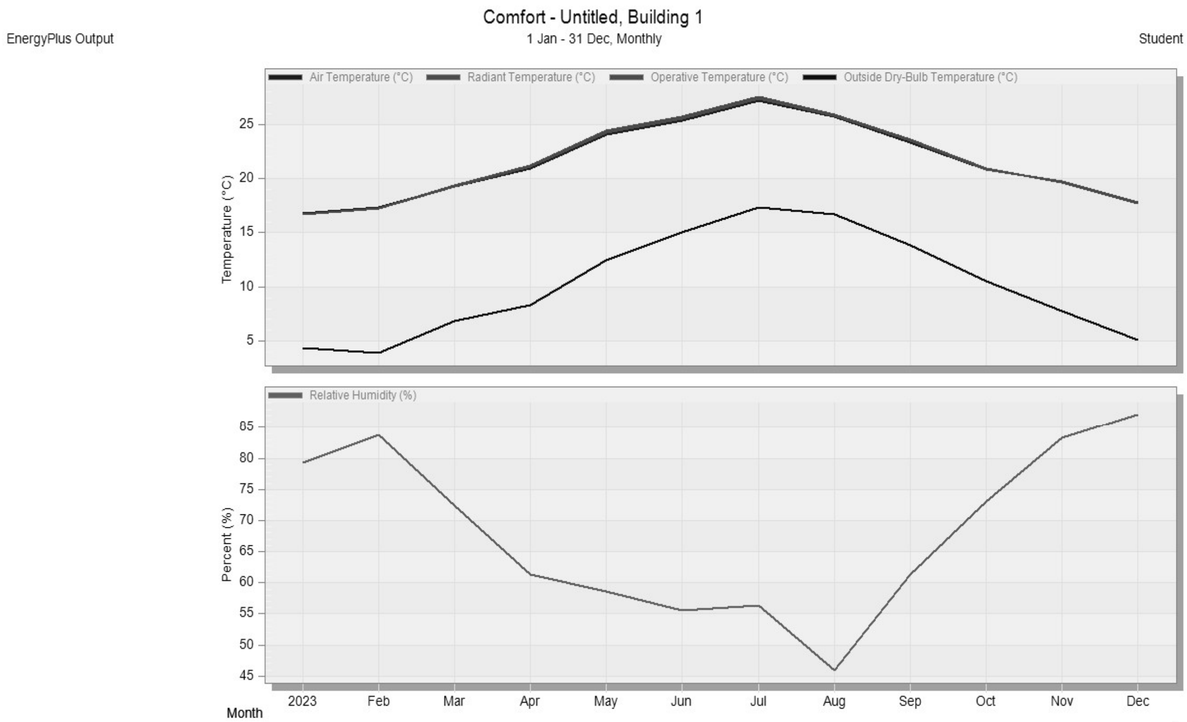
Figure 18. Sun path analysis (Authors via DesignBuilder). Image 7.5.3.1—Sun path analysis (Authors via DesignBuilder).

6.3. Simulations

Having input all the relevant data as mentioned above, the EnergyPlus simulation was run for a typical year, i.e., January to December.

The average temperatures throughout the year were 21.55 °C for air temperature, 21.68 °C for radiant temperature, and 21.61 °C for operative temperature. Monthly data reveals that January was the coldest, with minimum radiant and operative temperatures of 16.67 °C and 16.74 °C, respectively. July was the warmest, with maximum radiant and operative temperatures of 27.52 °C and 27.33 °C. These temperatures mostly align with the UK's Workplace (Health, Safety and Welfare) Regulations, which recommend internal temperatures between 16 °C and 26 °C. However, July may present a slight concern regarding heat (Figure 19). Consequently, relative humidity, of 87.10%, has the greatest effect in December, and the driest month is August with 45.99%. It is important to note that the building is used only at specific and limited times, especially during daylight hours, and for a short period of time, because it is a complementary space.

The natural lighting analysis, conducted under BREEAM accreditation, requires at least 80% of the net leasable surface in occupied spaces to be adequately illuminated during the day. Adequate illumination is defined by having an average daylight factor of at least 2.0% and either a uniformity index of at least 0.30 or a minimum spotlight factor of 0.80%. The simulation results show that the main classroom does not meet these BREEAM standards. However, since the classroom is used infrequently, comfortable lighting can still be achieved with the help of artificial lighting (Figures 20 and 21).



Month	2023	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Air Temperature (°C)	16.80	17.32	19.25	20.95	24.03	25.31	27.13	25.73	23.33	20.79	19.77	17.82
Radiant Temperature (°C)	16.67	17.22	19.34	21.19	24.40	25.69	27.52	25.90	23.58	20.89	19.67	17.73
Operative Temperature (°C)	16.74	17.27	19.30	21.07	24.22	25.50	27.33	25.82	23.46	20.84	19.72	17.78
Outside Dry-Bulb Temperature (°C)	4.40	3.94	6.84	8.32	12.47	15.01	17.31	16.72	13.85	10.56	7.82	5.11
Relative Humidity (%)	79.23	83.85	72.43	61.40	58.58	55.60	56.40	45.99	61.34	73.04	83.38	87.10

Figure 19. Thermal comfort monthly chart (Authors via DesignBuilder). Image 7.5.1.2—Thermal comfort monthly chart (Authors via DesignBuilder).

Summary Results	
Total area (m2)	54.3
Total area meeting requirements (m2)	0.0
% area meeting requirements	0.0
BREEAM Health and Wellbeing Credit HEA 01 Status	FAIL

Eligible zones for daylighting

Block	Zone	Floor area (m2)	Min DF (%)	Uniformity ratio (Min / Avg)	Average Daylight Factor (%)	Area Adequately Daylit (m2)
Block 1	Classroom	54.3	0.64	0.14	4.4	0.0
Total		**54.3**				**0.0**

Figure 20. BREEAM daylighting report (Authors via DesignBuilder). Image 7.5.2.1—BREEAM daylighting report (Authors via DesignBuilder).

The European paper and pulp industry produced 31.64 megatons of CO_2 emissions in 2014, although this represents a 43% decrease since 1990, reflecting increased efforts to address climate change [46]. These emissions result primarily from the combustion processes required for electricity and heat in papermaking. Wood, the industry's primary resource, is renewable and absorbs CO_2 as it grows [1], which suggests that paper could be a viable material for sustainable construction, although further research is needed to establish its credibility. In the specific case study, low annual energy consumption and CO_2 production were observed, with 494.93 kWh of energy and 256.87 kg of CO_2 produced annually, highlighting the sustainability of the project. It is important to note that energy sources such as a biomass boiler and photovoltaic panels were used [47]. The first is a fuel that generates heating through a renewable practice that burns local agricultural waste or wood pellets, reducing the environmental impact. The second captures sunlight and converts it into electricity, generating clean energy that directly powers systems such as lighting and electrical equipment in the classroom, reducing the demand on the conventional electricity grid and associated emissions.

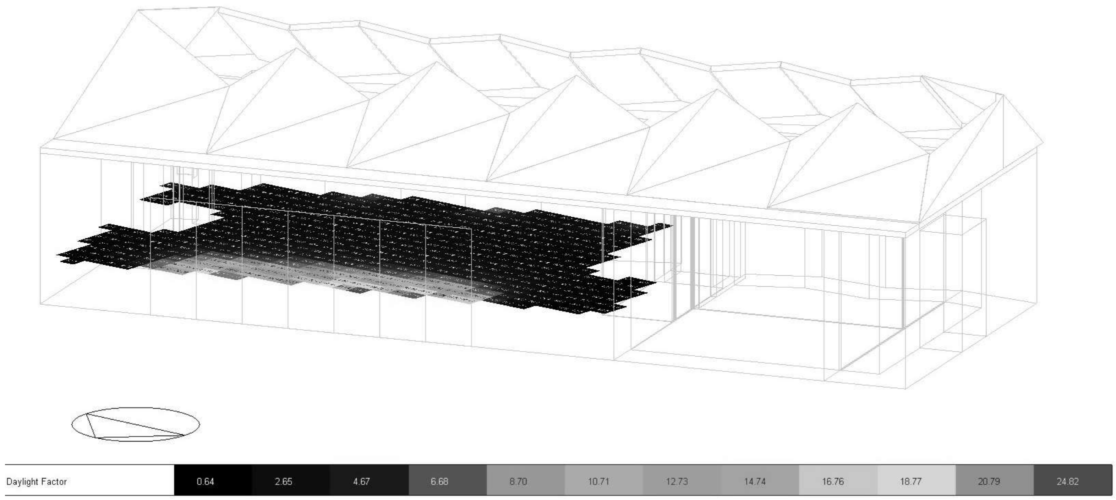
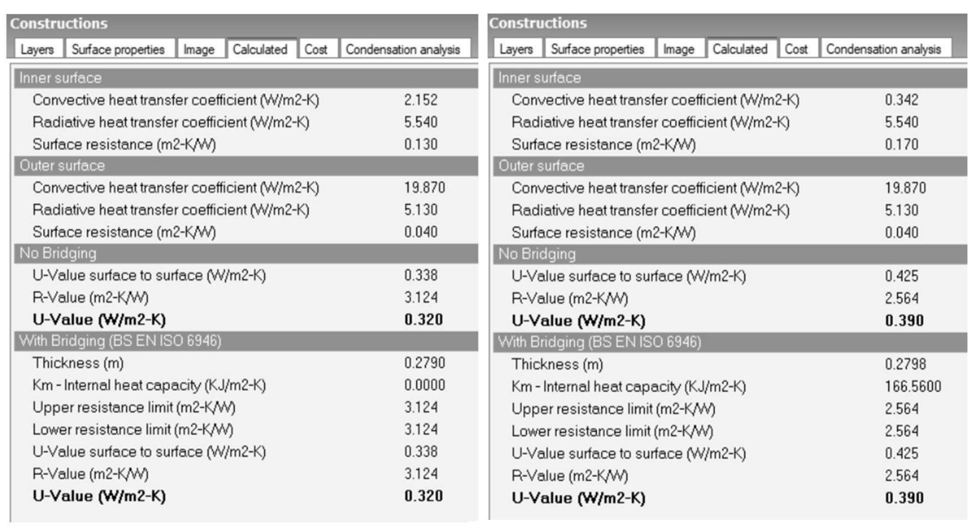


Figure 21. BREEAM daylighting analysis (Authors via DesignBuilder). Image 7.5.2.2—BREEAM daylighting analysis (Authors via DesignBuilder).

Regarding materials for the cardboard panels used to construct the walls and roofs, the following composition was considered: fibre-cement panels (outside), 6 mm solid board, 2 mm solid board, 50 mm honeycomb, 2 mm solid board, vapour barrier, and soft board on cardboard. With this composition, a U-value of 0.32 W/m^2 was achieved (Figure 22). Considering that the Building Regulations 2010 requirements for thermal performance of walls are to achieve a U-value of 0.26 W/m^{2}K [45], the cardboard panels do not meet standards; however, the building consumes 11% less energy than one built with traditional materials [1].



Constructions

Layers | Surface properties | Image | Calculated | Cost | Condensation analysis

	Wall	Floor
Inner surface		
Convective heat transfer coefficient (W/m2-K)	2.152	0.342
Radiative heat transfer coefficient (W/m2-K)	5.540	5.540
Surface resistance (m2-K/W)	0.130	0.170
Outer surface		
Convective heat transfer coefficient (W/m2-K)	19.870	19.870
Radiative heat transfer coefficient (W/m2-K)	5.130	5.130
Surface resistance (m2-K/W)	0.040	0.040
No Bridging		
U-Value surface to surface (W/m2-K)	0.338	0.425
R-Value (m2-K/W)	3.124	2.564
U-Value (W/m2-K)	**0.320**	**0.390**
With Bridging (BS EN ISO 6946)		
Thickness (m)	0.2790	0.2798
Km - Internal heat capacity (KJ/m2-K)	0.0000	166.5600
Upper resistance limit (m2-K/W)	3.124	2.564
Lower resistance limit (m2-K/W)	3.124	2.564
U-Value surface to surface (W/m2-K)	0.338	0.425
R-Value (m2-K/W)	3.124	2.564
U-Value (W/m2-K)	**0.320**	**0.390**

Wall U-value (Source by author via DesignBuilder)

Floor U-value (Source by author via DesignBuilder)

Figure 22. U-values of cardboard classroom materials (Source: Authors via DesignBuilder).

It is worth pointing out that foundations are still a challenging topic that needs further research since cardboard is not an appropriate material to fulfil these structural functions. In the case of the Cardboard Classroom, concrete foundations accounted for 85 tonnes of the building's total weight of 100 tonnes [1].

6.4. Summary of Results

The building maintains a comfortable average annual temperature of approximately 21 °C. Average temperatures comply with regulations, staying within a comfortable range between 16 °C and 26 °C.

Simulation results indicate that the main classroom does not meet BREEAM certification standards. However, its infrequent use allows artificial lighting to maintain a comfortable environment.

The building's orientation is strategically designed to control natural sunlight exposure. The south and west facades receive less light but are configured to prevent excessive illumination.

Since 1990, CO_2 emissions in Europe have progressively decreased by 43%, reflecting greater awareness and action against climate change. This case study demonstrates low annual energy consumption and reduced CO_2 production.

The building envelope, composed of cardboard and honeycomb panels, along with polyethylene and waterproof paper layers, provides thermal insulation and moisture resistance. An outer layer of fibre-cement enhances thermal properties, while vapour chambers and fire-resistant treatments were implemented to counteract moisture and improve safety.

Various studies confirm that paper, when used as an insulating material, outperforms traditional materials and is an environmentally attractive option. The cardboard panels used for the walls and roof achieve a U-value of 0.32 W/m^2K, meeting building regulation requirements. In terms of acoustic insulation, a reduction of 38 decibels is achieved.

While cardboard structures present challenges in foundation design, concrete foundations were used in this case to ensure structural stability.

7. Guidelines and Prototype

Lima possesses significant potential to harness sustainable practices within the construction sector. Adobe, a sustainable material historically prevalent in the region, has been a cornerstone of ancient Peruvian cultures and traditions, with some structures still standing as a testament to its durability.

In this context, cardboard is proposed as a modern evolution or reinvention of sustainable building materials in Peru. While it does present certain limitations, cardboard offers a wide range of advantages that make it an eco-friendly option, contributing to sustainable construction practices in the country (Figure 23).

In light of this, a set of guidelines is introduced, outlining different criteria and exposing benefits, disadvantages, and design recommendations to facilitate the incorporation of cardboard into sustainable architectural projects in Lima, Peru. Following this, an experimental exploration is conducted by designing a prototype cardboard building, adhering to the guidelines provided in the set of guidelines.

To develop the set of guidelines, the most prominent aspects investigated in this paper were taken into consideration, drawn from the study of the history of cardboard, its properties, and its contribution to architecture. This was followed by an analysis of the site, taking into account its cultural, climatic, and geographical characteristics. Subsequently, through the study methodologies implemented—such as three case studies (Japan, the Netherlands, and the United Kingdom), interviews, and questionnaires with professionals in the field (from Peru, England, and Poland), and energy simulations of an existing cardboard building—relevant results were obtained that served as a foundation for creating this set of guidelines.

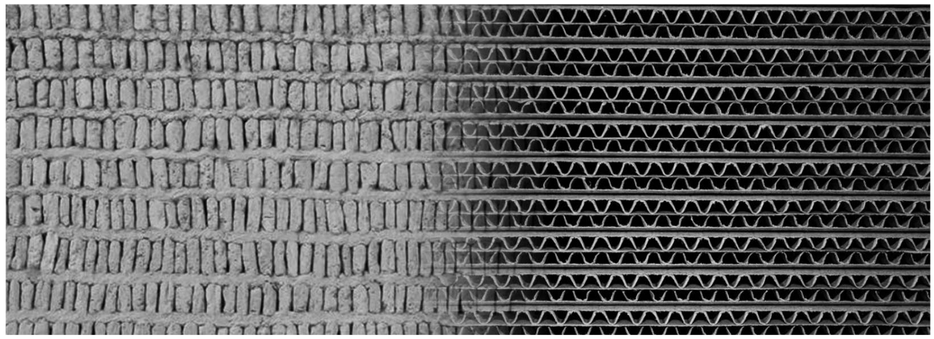


Figure 23. Sustainable material evolution in Peru—Adobe and cardboard (Source: Authors). Image 9.1—Sustainable material evolution in Peru—Adobe and cardboard (Source: Authors).

Among the topics of interest in the set of guidelines, the properties, structure, sustainability, and design parameters of cardboard as a construction material are highlighted, as well as the characteristics of the context of Lima, Peru. To develop this set, the guidelines were divided into two groups: limitations and discoveries, providing the interested party with specific references to develop architectural projects using cardboard as the main material (Figure 24).

7.1. Complementary Key Findings

Paper properties

- An optional solution is an outer layer of protective material like polyethylene, aluminium, impregnated boards, fibreboard, or plastic sheets.
- Use waterproof cardboard with additives in the pulp, which can be removed during repulping.
- Apply an external coating with polymer, aluminium foil, or additional cardboard during manufacturing.
- Avoid contact between cardboard and the ground to prevent moisture absorption and other issues.

Paper structure

- Cardboard's advantage in construction is its ease of demolition, disposal, and recycling compared to traditional materials.
- Natural and biodegradable fire protection, waterproofing, and adhesive technologies are not yet sufficiently developed.
- Paper properties vary widely due to different factors, making standardisation difficult

Sustainability

- Cardboard made from virgin fibres is 40% stronger than that made from recycled fibres.
- Demolishing cardboard buildings produces less waste compared to traditional buildings.
- Materials used for the foundations, joints, and reinforcements of cardboard structures can negatively impact the environment and create waste.

Design parameters

- Cardboard is best suited for temporary housing, exhibition spaces, or interior objects that do not require high durability or impermeability.
- To enhance security, consider wire mesh inside panels, multiple cardboard layers for better insulation, and an easily replaceable external layer for damage.

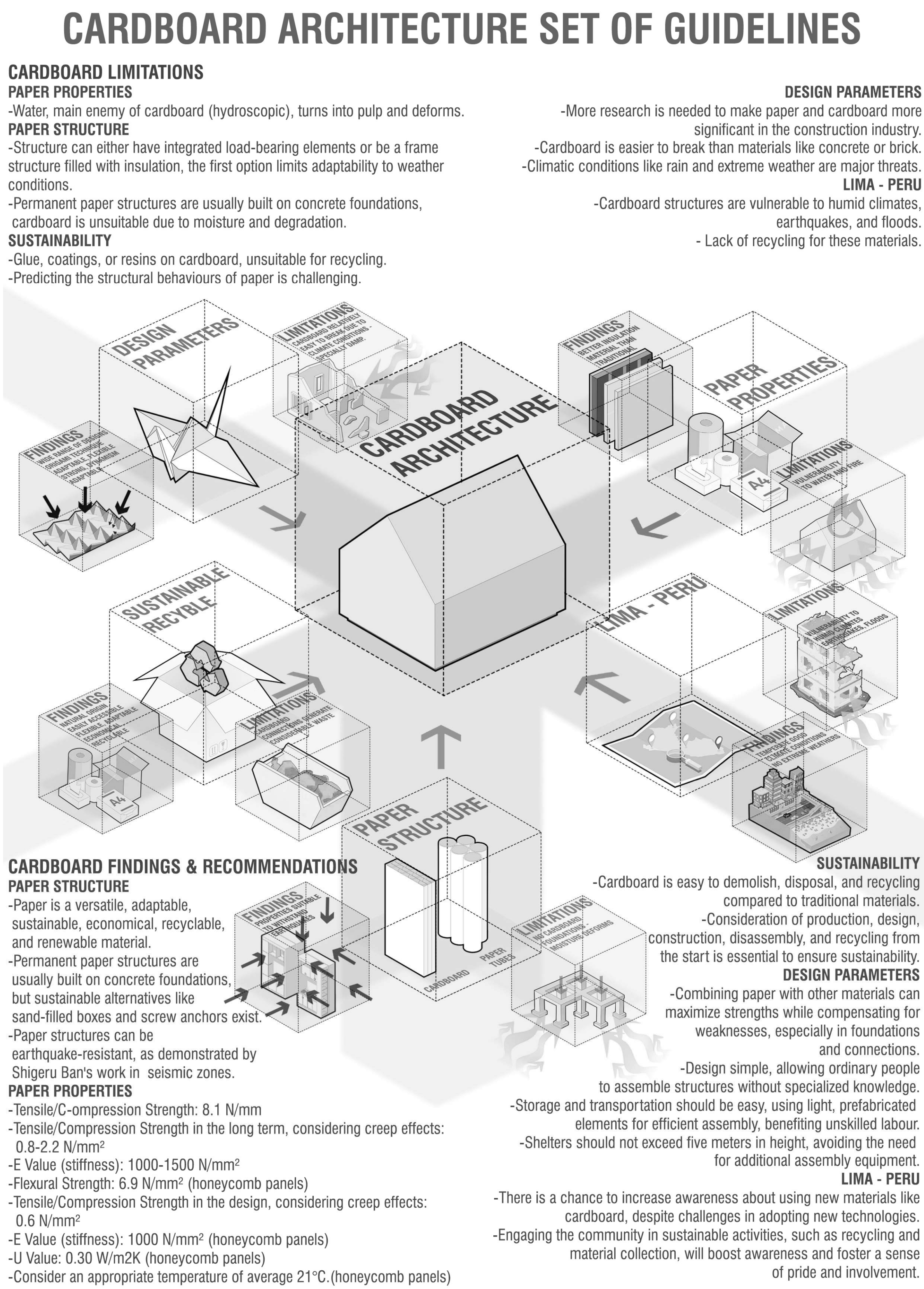


Figure 24. Set of guidelines (Source: Authors). Image 9.1—Sustainable material evolution in Peru—Adobe and cardboard (Source: Authors).

7.2. The Prototype

General design parameters:

- Use: housing
- Project area: 60 m^2–80 m^2
- Maximum height: one level, 5.80 m
- Maximum capacity: 4 people
- Location: Lima, Peru—low-income area
- Orientation: south
- Lifespan: 10 years and recyclable after use
- Materials: cardboard panels 150 mm for walls, roofs, and furniture; paper tubes for windows; wood and PVC profiles; wooden and melamine doors and shelves; wood and metal for joints.
- Environmental protection: fire, water, insulation, and acoustic treatment.
- Labour: unskilled work with previous and constant training—community involved.
- Ventilation: natural
- Lighting: natural + LED

An experimental prototype of a cardboard building is developed following the recommendations of the set of guidelines, considering both the limitations and the advantages. Having said that, a typology of a sustainable single-family residence for a low and middle socioeconomic level with basic needs is taken as a design template.

As design concepts, sustainability is applied through the primary material, cardboard, which is intended to be used for the majority of the prototype, with over 50% of it being recycled. Additionally, waste cardboard and other materials are collected at a zonal level. Other applied concepts include functionality, optimisation, dynamism, mobility, flexibility, and adaptability. Reference concepts such as "mobile design" and "flexible transport" are taken from the "Cabin Anna" project, developed by Caspar Schols [48].

The construction of each housing unit is proposed to involve community participation, without requiring specialised labour, but with the involvement of an expert to guide and train people in building the houses. This approach offers various benefits, such as fostering a sense of belonging and camaraderie within the community, as well as savings in logistics and construction, among others.

Moreover, the model considers the use of renewable energy, such as natural lighting, cross-ventilation, fog-water collection, and recycling, as well as thermal insulation and protection against humidity and fire. The building's projected lifespan is approximately 10 years, after which it can be demolished with a minimal carbon footprint, as nearly all of the materials can be recycled.

The architectural model has a simple volumetric form of a single story with a minimalist housing typology. It is orientated towards the south (considering that in Peru, the sun travels from east to west) and seeks to take advantage of renewable energy by using natural lighting through folding glass doors on the southern façade and circular windows (Figures 25 and 26). It also benefits from cross-ventilation and greywater collection through "fog catchers".

The building has the distinctive feature that its initial form (Figure 25) can be unfolded or extended in such a way that the interior spaces can be adapted in various ways to suit the inhabitant's preferences (Figure 26). Additionally, it has a roof inspired by origami folding systems, designed so that when folded, it opens a skylight that allows greater entry of natural light (Figures 25 and 26). The extension of the walls and roof operates via a mechanical system supported by rails, allowing the walls to slide and be pulled or pushed. The roof, meanwhile, can be manually operated using a steering wheel (Figures 25 and 26).

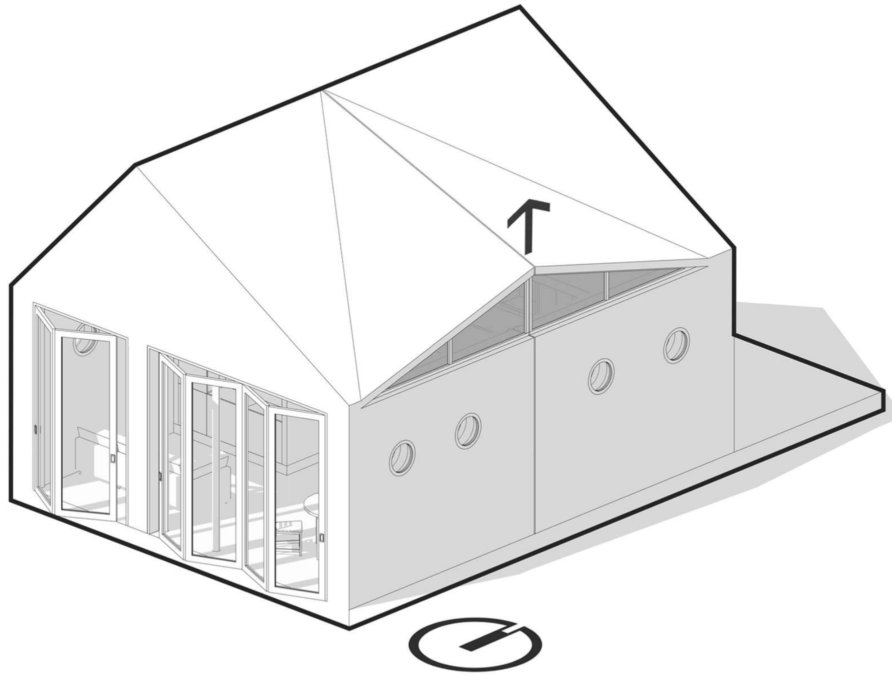


Figure 25. Prototype original form (Source: Authors). Image 9.1—Sustainable material evolution in Peru—Adobe and cardboard (Source: Authors).

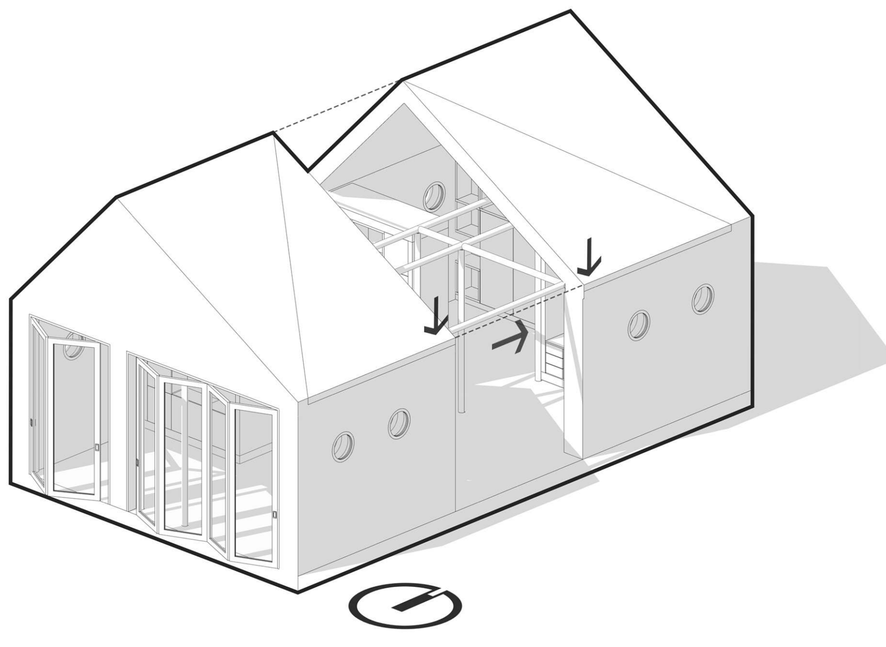


Figure 26. Prototype deployed (Source: Authors). Image 9.1—Sustainable material evolution in Peru—Adobe and cardboard (Source: Authors).

The building envelope is designed to protect against geographic conditions (high humidity, seismic zone), incorporating coatings and treatments for moisture and fire resistance, and considering that cardboard is a structurally resilient material. The U-values of the envelope are as follows: for the floor and roof, 0.39 W/m^{2}K, and for the walls, 0.32 W/m^{2}K.

The floor plan consists of a single level and is laid out in a rectangular shape measuring 6.90 m $\times$ 8.20 m, with an area ranging between 60 and 80 m^2 and a height of 5.80 m

(Figures 27 and 28). It includes four fixed spaces: the kitchen, dining room, bedroom, and bathroom. In the middle of these spaces are movable pieces of furniture made from corrugated cardboard, which serve as wardrobes, shelves, and drawers, and can be rearranged according to the occupant's preferences to create additional spaces, such as studies or living rooms. There is also a terrace located at the rear of the building (Figure 27).

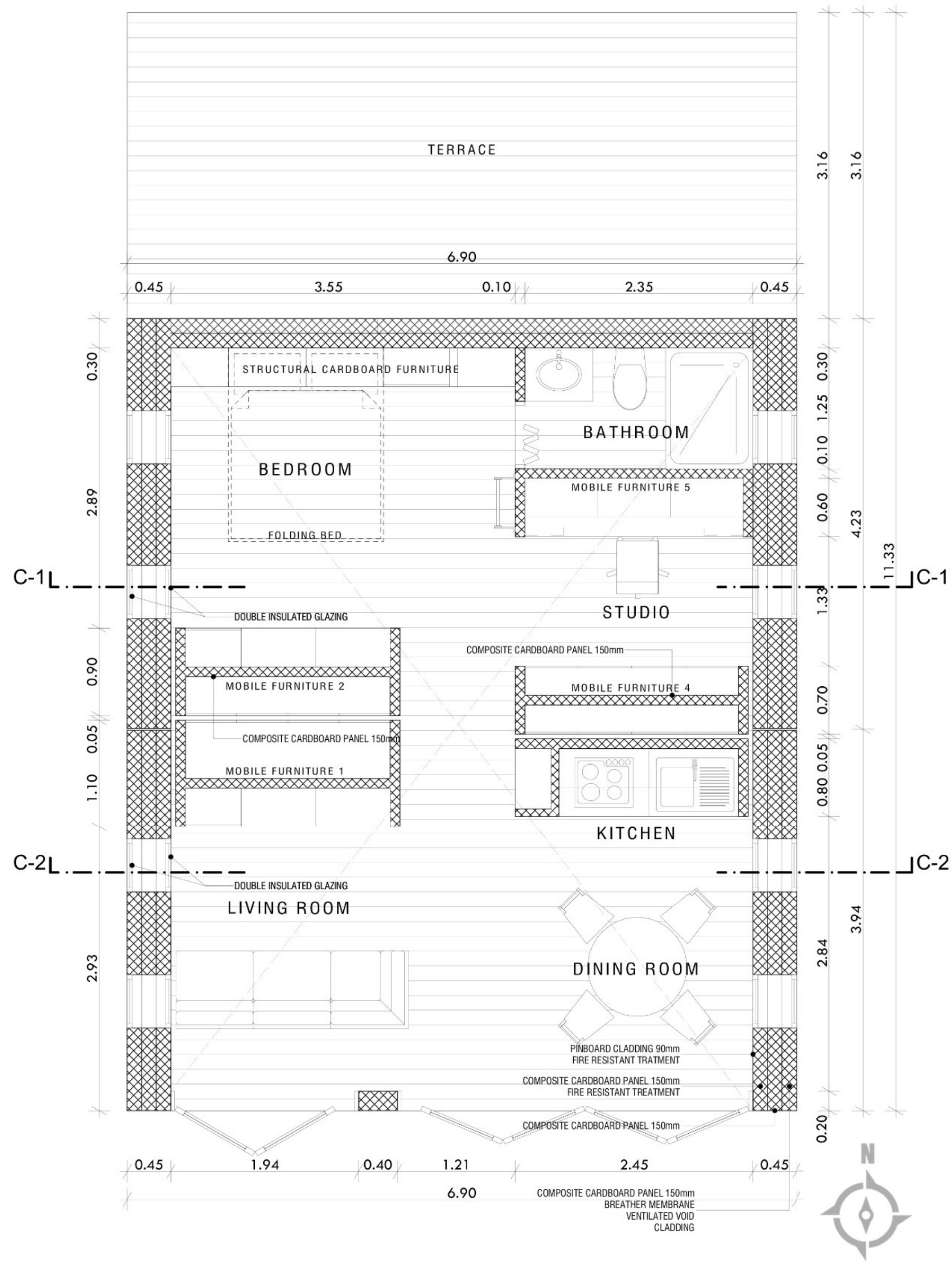


Figure 27. Prototype floor plan original form (Source: Authors). Image 9.1—Sustainable material evolution in Peru—Adobe and cardboard (Source: Authors).

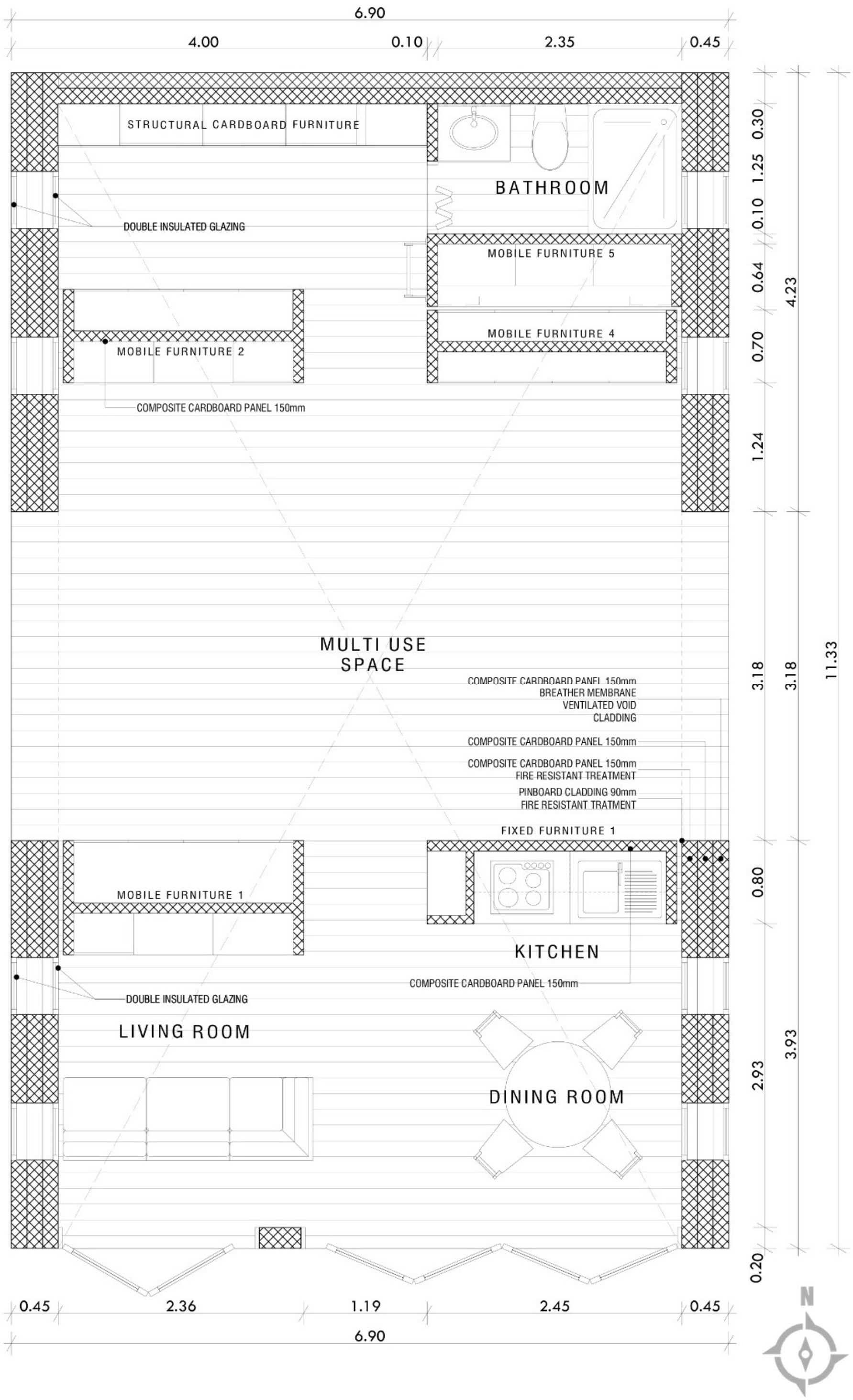


Figure 28. Prototype floor plan deployed (Source: Authors). Image 9.1—Sustainable material evolution in Peru—Adobe and cardboard (Source: Authors).

When the sliding walls are extended, a more elongated floor plan is created, reaching a length of up to 11.30 m. This provides greater flexibility for the multifunctional interior spaces and allows for increased natural lighting in open areas. It is worth noting that some furniture, such as beds, tables, and chairs, are foldable and can be stored within the movable furniture or the structural unit, with the aim of optimising space and ensuring that the layout can be easily adapted (Figure 28).

At the rear of the prototype, there is a fixed unit extending from floor to ceiling, which functions as shelving but also serves a structural purpose (Figures 29 and 30). The exterior walls consist of an outer layer of cladding, a breather membrane, a ventilated void, three 150 mm composite cardboard panels with fire-retardant treatment, and 90 mm of board cladding on the interior face (Figures 25–28). The roof is composed of an 8 mm Eternit board cladding, 38 × 50 mm counter battens, a breather membrane, another set of 38 × 50 mm counter battens, three 150 mm composite cardboard panels with fire-retardant treatment, and 90 mm of board cladding (Figures 29 and 30).

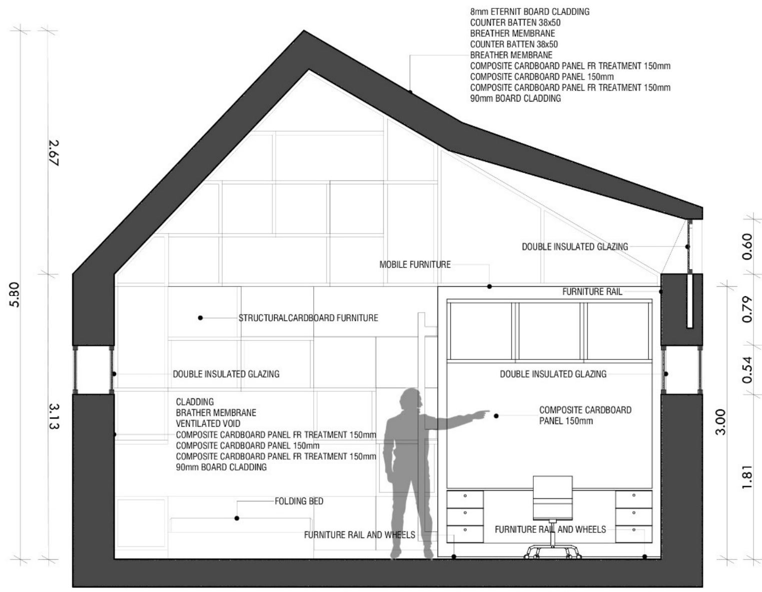


Figure 29. Prototype section 1 (Source: Authors). Image 9.1—Sustainable material evolution in Peru—Adobe and cardboard (Source: Authors).

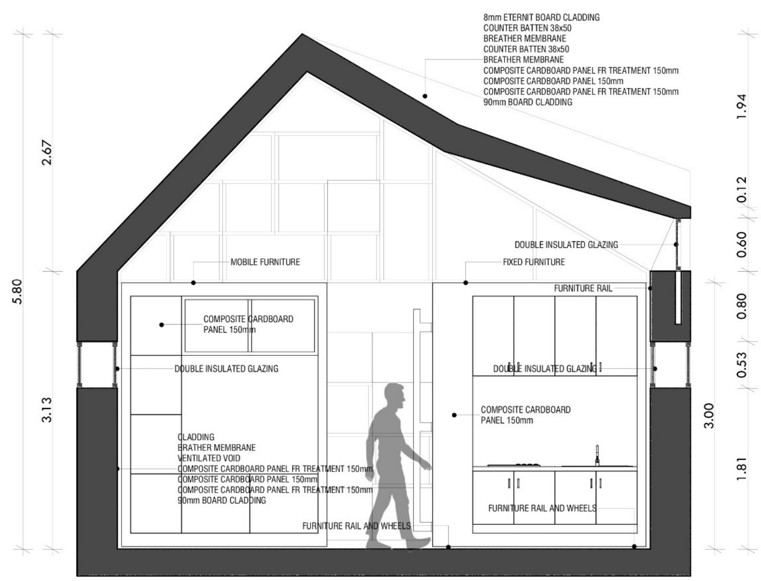


Figure 30. Prototype section 2 (Source: Authors). Image 9.1—Sustainable material evolution in Peru—Adobe and cardboard (Source: Authors).

The intention behind the dynamic activity of the inhabitant or inhabitants of the house is to maximise the use of a small space by optimising areas, considering that the context in which this prototype is used involves limited resources, confined spaces, and a low budget. For this reason, movable and adaptable interior spaces are employed, tailored to the user's needs. To achieve this, semi-open spaces are proposed, and the furniture or shelving units act as partition walls. Some of this furniture includes foldable tables, chairs, or beds, and it can be rearranged to create different environments (Figures 31 and 32).

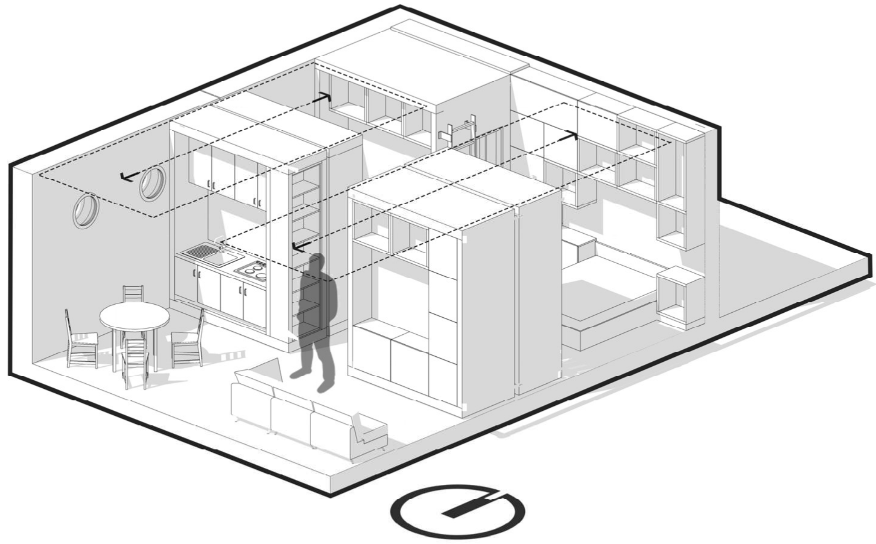


Figure 31. Prototype interior 1 (Source: Authors). Image 9.1—Sustainable material evolution in Peru—Adobe and cardboard (Source: Authors).

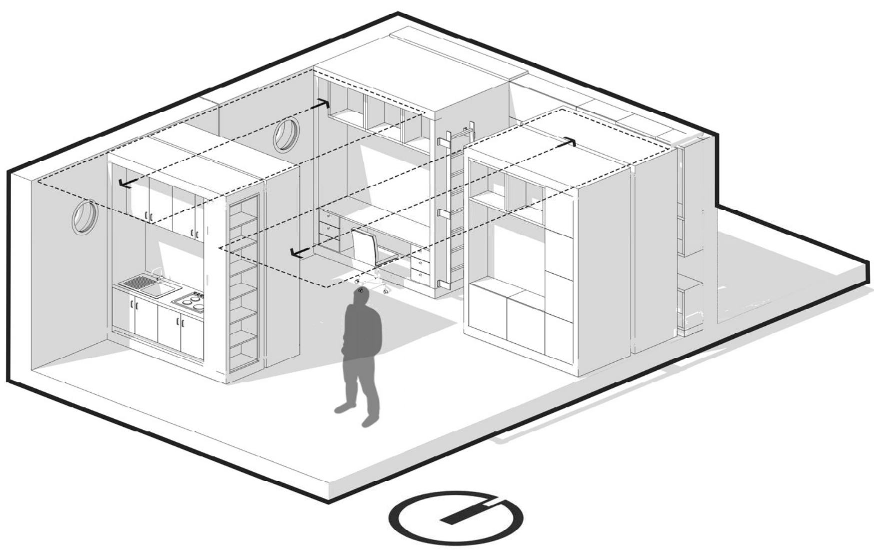


Figure 32. Prototype interior 2 (Source: Authors). Image 9.1—Sustainable material evolution in Peru—Adobe and cardboard (Source: Authors).

The system used to enable the mobility of the furniture consists of rails that allow manual movement. The windows are circular, as they are made from 60 cm diameter paper tubes. The only fixed furniture is in the bathroom and kitchen, as these areas contain water supply and drainage pipes.

8. Conclusions and Recommendations

The study on the use of cardboard as a construction material presents a series of important considerations regarding an element that is generally associated with temporary uses or packaging but has demonstrated notable characteristics such as recyclability, low cost, adaptability, and energy efficiency. These attributes position it as a viable resource for promoting environmentally friendly construction practices. With this in mind, the impact of cardboard as a construction material was analysed, highlighting several considerations that reflect both its potential and its limitations within the context of sustainable architecture. Based on this, the objective of the research was to develop a set of guidelines and an architectural prototype that would provide professionals with better tools and knowledge for the implementation of cardboard in the field of sustainable architecture and construction, specifically in Lima, Peru. A mixed-methods research approach was employed to gather information, which included three case studies from Japan, the Netherlands, and the United Kingdom, along with online interviews and surveys of architects from Britain, Poland, and Peru.

Additionally, dynamic thermal simulations were conducted on an existing school building in the UK that used cardboard as its primary construction element. The result was an annual energy consumption of 494.93 kWh and a CO_2 production of 256.87 kg, which reflects a positive impact on the project. The material was used in the walls, roof, and structure, complemented by recycled materials such as wood. Moreover, off-site cardboard panel manufacturing contributed to reducing waste and maintaining order and cleanliness on the construction site. The carbon footprint was also reduced by avoiding additional transportation, and the involvement of the school community in collecting cardboard for recycling further supported sustainability.

Among the key findings of the study, it can be concluded that while cardboard has been successfully used in buildings (mostly temporary) and experimental projects, in Lima and other regions with similar characteristics, the use of traditional materials such as concrete, steel, or wood is still prioritised due to their perceived reliability and durability. One of the main obstacles identified through interviews and surveys was the persistent negative perception of cardboard. It is primarily associated with being a disposable and weak material, which fosters distrust among architects, engineers, and the general population. This perception, partially driven by a lack of information, limits its inclusion in architectural projects on a global scale.

On the other hand, as a lesson learnt and from a technical point of view, when used as a thermal insulation, this element outperforms other conventional materials due to its cellular structure, which traps air, a poor conductor of heat. In contrast, materials such as concrete, brick, and steel, being denser, have higher thermal conductivity, allowing heat to transfer more efficiently. Additionally, cardboard is significantly lighter than steel or concrete, making it easier to handle and transport while also reducing its environmental impact. Although cardboard is not as structurally robust as traditional components, combining it with recycled materials can enhance its thermal performance without compromising stability. Furthermore, when recycled, cardboard has a substantially lower environmental impact than products requiring significant energy in their production, helping to reduce the building's carbon footprint.

In contrast to the thermal benefits, this material also has certain limitations that make it difficult to use on a large scale in permanent structures. One of the main deficiencies observed is its vulnerability to elements such as humidity and fire, which pose serious challenges in humid climates such as Lima's. While there are treatments and coatings that can improve the resistance of cardboard to these elements, further research is needed to develop effective solutions that extend its useful life without compromising its sustainability.

Furthermore, it can be asserted that, in the context of Lima, considering its geographical and climatic characteristics, a cardboard building should be limited to a single story if a structure is proposed that predominantly uses this material. However, if it is used as a complementary material within a hybrid system alongside other conventional and more resilient materials such as steel, concrete, or wood, it becomes a satisfactory and reliable option, which is increasingly being applied in the construction sector. In terms of constructing taller buildings, the situation could change in the future with more research and greater advancements in the field.

Finally, the document proposes that cardboard should be the successor to adobe as a sustainable material in the field of construction in Peru (Figure 23). However, the context presents various challenges. Political, economic, and social instability complicate the implementation of bold and innovative projects. Moreover, the limited promotion of initiatives, regulations, and construction standards focused on environmental factors contributes to negative and challenging scenarios for implementing and popularising sustainable strategies in this region. To advance the aforementioned proposal and raise greater awareness of climate change, a thorough analysis of the context is needed, considering its benefits and weaknesses, complemented by a multidisciplinary approach that combines scientific research with practical experimentation, where cardboard can undoubtedly play a crucial role in the sustainable architecture of the future. For this potential to materialise, the involvement of stakeholders—whether architects, engineers, designers, regulators, or society at large—would be essential, contributing knowledge, review, research, opinion exchanges, and synergies that lend greater validity and weight to the study. Only in this way can a framework of policies and actions be established that fully capitalises on the potential of this material to build more sustainable, resilient, and environmentally conscious cities. It is only through technical validation, supported by solid data and tangible results, that the current distrust and doubts can be overcome.

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