8 Paper and cardboard as sustainable materials

Cardboard is generally regarded as an eco-friendly or 'green' material. The sustainability of cardboard as a building material can be researched from different points of view, and different aspects should be taken into account. To answer the question as to whether cardboard is a 'green' or sustainable material for building applications, we must first define the meaning of these words. Next we need to research the various types of impact cardboard used as a building material may have on the environment.

The word 'green', in relation to buildings, is open to many interpretations. In many cases the word 'green' is used for marketing purposes. Cardboard products, in particular, can easily be called green because of their eco-friendly appearance. Take, for example, furniture made out of cardboard, which is often described as sustainable. Generally speaking, this type of furniture is very expensive, which means that only wealthy people will be able to afford it, which is in contradiction with one of the main tenets of sustainable development.

As Robert and Brenda Vale, quoted by Wooly et al., [1] stated: '[a] green approach to the built environment involves a holistic approach to the design of buildings; that all the resources that go into a building, be they materials, fuels or the contribution of the users, need to be considered if a sustainable architecture is to be produced.'

The phrase 'sustainable development' has a much broader interpretation. The author of this dissertation adheres to the narrower definition. Sustainable development in general means that current development meets the present needs without compromising the ability of future generations to meet their own needs. Sustainable development has two highlighted concepts: the concept of the essential needs of the world's poor, which should be fulfilled as a matter of priority, and the idea of limitations imposed by the state of technology and social organisations on the environment's ability to meet present and future needs. [2]

Sustainable construction improves the life cycle of building by lengthening the lifespan of building components, increasing the flexibility of the functional and spatial layout of buildings and their potential changes, and promoting the recycling of materials and products after a building has been demolished.

The life cycle of a building consists of four stages: pre-construction (Stage I); construction (Stage II); post-construction (stage III) and demolition (stage IV).

It follows that the entire cycle of materials consists of the following stages: production, construction, usage, demolition, recycling, reusing processes or final disposal.

The total life-cycle energy use of building includes both operating energy and embodied energy. [3] Operating energy includes the energy used to maintain the inside environment through processes like heating, cooling, lighting and operating appliances. With regard to operating energy, materials can be rendered more sustainable by ensuring they have a higher thermal insulation value or greater thermal mass. But the most important factor with regard to operating energy is that the project take into account the local natural conditions and adapt to them.

Higher sustainability can be achieved by reducing the use of raw materials and reducing the loss of resources during the production and construction processes and throughout the life of the building. It can be also improved by recycling of the used materials, in such a way that recycled materials can be used again at their original level of quality.

Life Cycle Assessment is a method used to measure and evaluate the environmental impact of product systems or activities by describing and assessing the energy and materials used and released into the environment over the course of a building's life cycle, from cradle to grave.

The assessment of the environmental performance of cardboard as a building material is based on the following environmental categories proposed by M. Vaccari in her dissertation. [2]

- Resources: extraction of raw materials, water and minerals
- Recyclability of the material
- Energy use in production, embodied energy and operating energy
- Durability and maintenance
- Global warming, climate change and emissions to soil, air and water.

§ 8.6.1 Resources

The main raw materials used in the production of paper are wood pulp and recycled paper. In addition, a large amount of water is used during paper production, but this water is then recovered and reused or returned to the source from which it was extracted. Although the paper industry uses a large amount of water, only a small part of it is actually 'consumed'. The rest of the water used in this process can be re-used. In 2012, 92 percent of used water was given back to the environment. [4]

Wood harvesting will always have an impact on the environment. Therefore, it is important to use wood resources from certified, well-managed and well-regulated sources. The International Council of Forest and Paper Associations (ICFPA) and its members are committed to sustainable development to ensure that environmental, social and economic benefits are available to current and future generations. ICFPA commits its members to Sustainable Forest Management (SFM) and sustainable forest cultivation across a range of forest types and landscapes to meet society's growing needs. [5] ICFPA has released two policy statements: SFM certification and Forest Plantations.

Between 2000 and 2013, the percentage of certified ICFPA industry-managed forest supply areas increased from 11% to 52%. In European countries, 82% of raw materials are sourced in Europe and come from responsibly managed forests. [4]

§ 8.6.2 Recycling

The other main resource for the production of paper is recycled material. The recycling process is similar to the production one, but also includes cleaning of the fibres. Depending on the grade of the paper being produced, some virgin fibres can be added. A life cycle analysis demonstrated that recycling paper only requires one-sixth to one-third of the amount of energy required to produce new paper, requires less than half as much water, produces far fewer greenhouse gases and releases much fewer toxic chemicals into the air and the water than producing paper from virgin fibres. That said, recycling may require more energy because used paper has to be transported to recycling plants. On the other hand, the wood industry consumes a lot of energy when logging and transporting wood to factories, and paper that is not recycled has to be transported to a landfill site. Use of recovered fibres to produce paper may energy consumption by 23% to 74%, reduce air pollution by 25%, reduce water pollution by

65% and use 58% less water compared to the use of virgin fibres for paper-making. [2] The recycling rate in CEPI countries increased from 40.3% in 1991 to 71.7% in 2014. [6] It is important to note that fibres can only be re-used up to five or six times, because the fibres grow shorter during the recycling process and lose their strength. Cardboard products made out of recycled paper are approximately 40 percent weaker than those made out of virgin paper, as Mick Eekhout demonstrated during the tests he carried out as part of the Cardboard Dome project. [7]

Cardboard is a building material that can be easily recycled. However, its use requires additives, fillers, coatings and adhesives that improve the strength and impregnation of the cardboard, which may prevent the building materials from being recycled. Some coatings have to be mechanically removed. The pavilion built for Wroclaw University of Technology provides a good example of the impact impregnation agents can have on cardboard. Paper tubes exposed to natural conditions were impregnated with yacht lacquer. After the demolition of the pavilion, the paper tubes were supposed to be recycled, but the paper mill refused to accept them because of the severity of the impregnation agents used.

The paper building of Westborough School, designed by Cottrell and Vermeulen Architecture and engineered by BuroHappold, originally supposed to be made out of 90% recycled materials and to be 90% recyclable. However, this proved infeasible due to the large volume of material used for the foundations. The foundations made up 85% of the weight of the whole building, while constituting 46% of its volume. Apart from the concrete, 56% of the material (by volume) consisted of recycled material, and the same amount is recyclable. [8]

§ 8.6.3 Energy use in production

Pulp and paper production is energy-intensive. Energy consumption accounts for approximately 16% of the production costs.

Generally speaking, there are two methods by which pulp is produced: chemical and mechanical (see Chapter 2). Chemical pulp production requires two to three tonnes of wood to create one tonne of pulp. Mechanical pulp production requires approximately 1.1 tonne of wood to create one tonne of pulp. When chemical production methods are used, the wastes is burned and the energy produced is enough to run the mill and sometimes to produce extra heating or electricity. Mechanical production methods require more externally sourced energy, but do not require as many trees. As shown in

Chapter 2, chemical pulp is lignin-free. As a result, it is stronger and more suited to the production of strong packaging paper.

In the year 2013, 57.1% of the total energy consumption of the European pulp-and-paper industry concerned biomass fuels. Since 1991, primary energy consumption in the paper industry has decreased by 17.5%. Total electricity consumption increased by about 17% from 1991 onwards, but the trends showed a decrease in energy consumption by 9% in 2013 due to measures such as improved process technology and investments in combined heat and power (see Fig. 7.75). [6]

Specific carbon dioxide emissions (kt CO_2 / kt of product) from fossil fuels decreased by 50.6%.

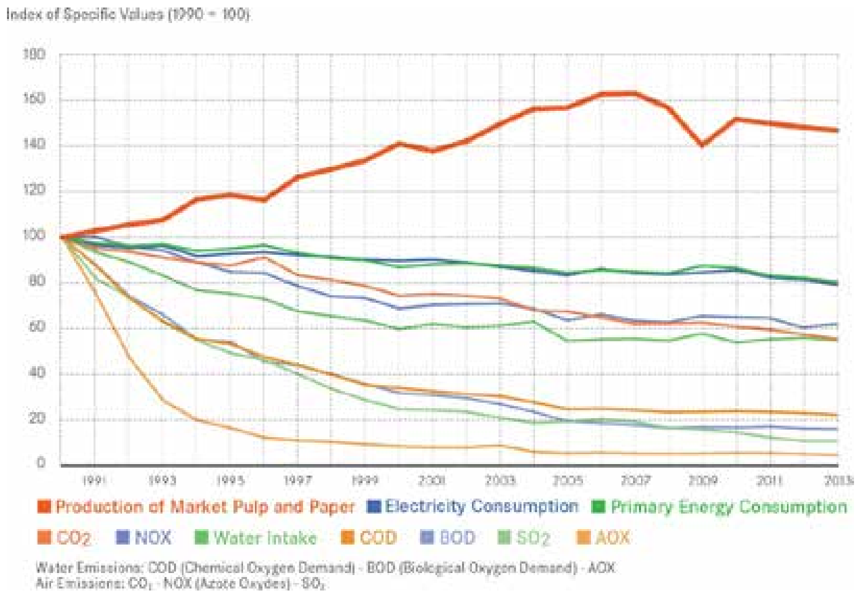

FIGURE 8.1 Evolution of Environmental Impacts of the CEPI Pulp and Paper Industry

§ 8.6.4 Embodied energy

The building sector is responsible for more than one-third of global greenhouse gas emissions. Buildings are responsible for more than half of global energy consumption. A significant proportion of the energy consumed by a building over its life cycle is the energy embodied in the materials used for construction and the energy used during construction. Off-site production processes of building material uses up to 75% of the total embodied energy in the building.

The total life cycle energy of a building includes both operational energy and embodied energy. Operational energy consists of heating, cooling, lighting, ventilation and operating appliances. Operational energy consumption can be decreased by using energy-efficient appliances and advanced insulating materials. [3]

Embodied energy is the energy consumed by the processes associated with the production of all the elements and components that make up a building, from mining and processing of natural resources to manufacturing, transport and product delivery.

Embodied energy is expended once during the initial stage of construction, while operational energy is used continuously over the effective life of the building. The Commonwealth Scientific and Industrial Research Organisation demonstrated that the embodied energy contents of an average household in Australia are nearly equivalent to fifteen years' worth of operational energy. [3]

Transportation issues may have a significant impact on the embodied energy of the paper-based products used in architecture. The distance raw materials travel to a paper plant, and from there to a producer of paper-based products (tubes, corrugated board, honeycomb panels, etc.), and from there to the place where the components are prefabricated, and then finally to the building site, may vary depending on the local situation.

	EMBODIED ENERGY MJ/KG			EMBODIED CARBON – KG CO_2E/KG
	Minimum	Average	Maximum	
Paper	5.18	27.75	61.26	
Paper, Cardboard	10.70	29.97	60.00	
Predominately recycled	13.20	25.66	35.27	
Virgin	35.50	35.50	-	
Paperboard (general construction use)	10	24.80	39	1.29
General Clay Bricks	0.63	3.0	6.0	0.24
Lime	4	5.3	9.1	0.78
Steel	6	29.36	77	
Timber	0.30	9.43	61.26	0.31fos+0.41bio

TABLE 8.1 Embodied energy in materials [6]

Cardboard is a highly energy-intensive material. Paper and cardboard consisting of predominantly recycled fibres are less energy-intensive than paper and cardboard consisting of virgin fibres.

If we compare the embodied energy levels of typical construction materials, we can see that cardboard used for construction purposes is over eight times more energy-intensive than bricks, almost seven times more energy-intensive than lime, 2.6 times more energy-intensive than wood, and only 12% less energy-intensive than steel (see Tab. 7.5).

Embodied energy is usually quoted per unit of weight or volume. Therefore, building elements or components made of different materials will differ in weight per volume. It is important to take this consideration into account when determining the embodied energy per building element.

As cardboard is a lightweight material, a wall component made of typical materials is a lot less energy-intensive than the wall panel proposed by Vaccari (made of 5mm corrugated cardboard on the outsides and a 25mm honeycomb panel on the inside, held by a timber frame) (see Tab. 7.6). [2]

WALL SYSTEM	EMBODIED ENERGY (MJ/M^2)
Timber frame, timber clad, painted	188
Timber frame, brick veneer, unpainted	561
Double brick, unpainted	860
Steel frame, fibre cement clad, painted	460
Cardboard panel: corrugated cardboard 5mm, honeycomb panel 25 mm, timber frame	70 (minimum) 189 (average) 403 (maximum)

TABLE 8.2 Embodied energy in different types of walls [9]

When average embodied energy is taken into account, the combination of the cardboard wall panel and the timber frame is the least energy-intensive. If the maximum embodied energy of the cardboard panels is taken into account , the cardboard wall panel is the second least energy-intensive, is less than half as energy-intensive as a double brick wall and 14% less energy-intensive than a steel frame. .

§ 8.6.5 Operating energy

Operating energy is the energy used for maintaining the inside environment. Operating energy is consumed by lighting, cooling and heating systems and operating appliances. Operating energy consumption can be reduced by better thermal insulation and by good design which takes into account the properties of various thermal insulation materials and rules out thermal bridges.

In order to compare different materials and different cardboard building components and their influence on the energy efficiency of a building, a comparison of wall elements used in several projects involving cardboard architecture is provided below. U-values (i.e., heat transfer coefficients) are compared in order to clarify increases and decreases in operational energy consumption with regard to different material solutions. A building's U-value represents its energy loss during the operation stage.

PROJECT NAME	WALL STRUCTURE (LAYERS)	U-VALUE
Paper Log House [9]	100 mm diameter cardboard tubes, 4 mm thickness of the wall, length 2 m	2.13 W/m² °C
West Borough Cardboard School [9]	Panels: fibre cement panels (outside), 6 mm solid board, 2 mm solid board, 50 mm honeycomb, 2mm solid board, vapour barrier, soft board on carton	0.32 W/m² °C
Cardboard Dwelling in Brazil [9]	Corrugated cardboard (5mm), Honeycomb Panel (25mm), Recycled Tetra Pak boards	0.53 W/m² °C
TECH		

TABLE 8.3 U-values of different types of cardboard walls [2]

Mirian Vaccari in her research used IES Virtual Environment 5.8.1 software to assess the environmental performance of her own design, the designs of Shigeru Ban (Paper Log House) and the paper building of Westborough School designed by Cottrell and Vermeulen Architecture See Tab. 7.7)

Özlem Ayan in her research used the SimaPro simulation platform and OGIP software in order to assess the environmental and ecological performance of cardboard buildings. Ayan compared functional wall samples with an area of 1m² composed of a corrugated cardboard core with a thickness of 100mm and four different finishing materials (steel plate, aluminium plate, plywood and glass-fibre-reinforced plastic) with wall samples of conventional building materials (brick wall and lightweight concrete wall) with an area of 1m² and a thickness of 200mm (see Tab.7.8). [10]

FUNCTIONAL WALL UNIT 1 M²	WALL STRUCTURE (LAYERS)	U-VALUE
Steel facing	Steel finishing layer 0.5 mm, glue, corrugated cardboard core 100 mm, glue, steel finishing layer 0.5 mm	0.9 W/m^2 °C
Aluminium facing	Aluminium alloy layer 1 mm, glue, corrugated cardboard core 100 mm, glue, aluminium alloy layer 1 mm	0.9 W/m^2 °C
Plywood facing	Plywood outdoor use layer 5 mm, glue, corrugated cardboard core 100 mm, glue, plywood outdoor use layer 5 mm	0.85 W/m^2 °C
GFRP facing	Glass fibre reinforced plastic layer 3 mm, glue, corrugated cardboard core 100 mm, glue, glass fibre reinforced plastic layer 3 mm	0.79 W/m^2 °C
Brick wall, Swiss module	Brick 200 mm	2.20 W/m^2 °C
Lightweight concrete wall	Lightweight concrete blocks 200 mm	0.95 W/m^2 °C

TABLE 8.4 Comparison of cardboard composite sample vs. conventional samples (per $1m^2$) [7]

Comparison of cardboard composite sample versus conventional samples (per $1m^2$) [10]

In the prototype of TECH 01, the U-values of the wall panels were as follows:

- Boundary conditions:
- Exterior temperature: -18 °C
- Interior temperature: 21 °C
- Delta T: 39

WALL COMPOSITION	U FACTOR	LENGTH	THICKNESS
Sample 1 3mm cardboard, six 25mm honeycomb cardboard panels, 3mm cardboard	0.2523 W/m^2K	203.5mm	156mm
Sample 2 3mm cardboard, seven 25mm honeycomb cardboard panels 3mm cardboard	0.2180 W/m^2K	203.5mm	181mm
Sample 3 3mm cardboard 3mm cardboard, eight 25mm honeycomb cardboard panels, 3mm cardboard	0.1915 W/m^2K	203.5mm	206mm

TABLE 8.5 TECH 03 U-value simulation

§ 8.6.6 Durability and maintenance

The environmental impact of a building is affected by the duration of the building's life and its individual parts. The expected lifespan of the cardboard house designed by Ayan is estimated at ten to fifteen years. [10]

The cardboard structure of Westborough School, designed by Cottrell and Vermeulen Architecture and constructed by BuroHappold, was estimated to have a twenty-year lifespan. The 'after-school clubhouse', which was built in 2001 out of cardboard elements (paper tubes and cardboard wall panels), is still in use today, sixteen years later. [8]

Many building materials and components have short maintenance intervals. There are two possible methods to handle the environmental impacts of buildings: prolonging the lifetime of a building and choosing materials that use less energy. As far as cardboard structures are concerned, the latter option will provide better results. [10]

It is difficult to estimate the maximum lifespan of buildings composed of cardboard components, because only a few of the currently available examples were built as permanent structures. Judging from those examples, cardboard buildings can be assumed to have a lifespan of fifteen to twenty years.

§ 8.6.7 7.5.8. Emissions

Construction activities and paper-making not only consume energy but also cause environmental pollution and emission of greenhouse gasses.

§ 8.6.8 CO_2 emissions

The European pulp-and-paper industry was responsible for 31.64 megatonnes of direct CO_2 emissions in 2014. Since 1990, the specific CO_2 emissions per kilotonne of product have fallen by 43%, which is a major achievement in the current harsh and competitive climate. [4] These CO_2 emissions are mainly caused by combustion processes: the production of electricity and heat needed for the paper-making process. The industry's main resource (wood) is renewable and absorbs CO_2 while growing. [15]

§ 8.6.9 Emissions to air and water

Wastewater effluents from pulp and paper mills contain mainly solids, nutrients (nitrogen and phosphorus) and organic substances. Between 1990 and 2012, the BOD (biological oxygen demand, i.e., concentration of organic substances in the water) per tonne decreased by 83%. This helped combat the problem of oxygen depletion of surface water. Specific AOx (organic chlorine compounds) was decreased by 95% in the same period due to new bleaching methods.

SO_2 (sulphur dioxide) and NO_x (nitrogen oxides) emissions, being by-products of energy consumption, were decreased by 88.8% (SO_2) and 38.4% (NO_x), respectively, between 1990 and 2012. Both SO_2 and NO_x were responsible for acidification of the water. [4]

Vaccari compared the energy efficiency simulations of three structures designed as cardboard buildings similar in shape but built with traditional materials. The comparison involved the Paper Log House by Shigeru Ban (built in 1995), Westborough School by Cottrell and Vermeulen Architects and BuroHappold (built in 2002) and Vaccari's own project (not realised). Each of these three buildings was simulated in IES Virtual Environment 5.8.1 software as a cardboard structure and a traditional one. [2]

Paper Log House simulation, location – Kobe, Japan

U values of the original project estimated using the project's specifications and IES [2]:

- U-value (walls)2.13 W/m^2 °C
- U-value (floor) 0.79 W/m^2 °C
- U-value (roofing) 4.63 W/m^2 °C

The simulation for the Paper Log House shows that the original design built in Kobe is more energy-intensive in use than a similar building constructed with traditional materials. However, if the paper tubes had been filled with paper-based insulation material, as was done in Turkey (see section 4.3.4), the energy consumption of the building would have been reduced by 20%..

West Borough Cardboard School simulation, location – Westcliff on Sea, UK

U values of the original project estimated using the project's specifications and IES [2]:

- U-value (walls) 0.32 W/m^2 °C
- U-value (floor) 0.39 W/m^2 °C
- U-value (roofing) 0.32 W/m^2 °C

The original building shows better energy performance than the one which would have been built using traditional materials. The original project is 11% less energy-consuming than a traditional one.

Cardboard dwelling in Brazil, location Sao Paulo

U values of the original project estimated using the project's specifications and IES [2]:

- U-value (walls) 0.53 W/m^2 °C
- U-value (floor) 2.31 W/m^2 °C
- U-value (roofing) 5.15 W/m^2 °C

The simulation of the version of the building built using traditional materials was based on the model of a Brazilian low-cost dwelling. Vaccari's Cardboard Dwelling consumes 22% less energy than a traditional dwelling.

Vaccari estimated the lifespan of her cardboard structure to be ten years. A comparison of the energy required for cooling the Cardboard Dwelling and its embodied energy and the energy required and involved in traditional solutions shows that the cardboard structure is 2,733 kWh/year more efficient than a traditional dwelling. In about three years, the energy savings gained by the cardboard building would offset the amount of embodied energy inherent in the cardboard house. [2]

Compared to other materials, cardboard performs well in terms of energy efficiency.

§ 8.1 Conclusions

The main raw materials for the production of cardboard are renewable or recycled fibres. This makes cardboard an attractive material from an environmental point of view. The global paper industry, but particularly the European paper industry, has made a great effort in the last few years to make the production of paper and cardboard more sustainable. Over 57% of the energy used in paper mills comes from bio-resources.

Cardboard made from virgin fibres is more energy-intensive than cardboard made from recycled fibres. However, cardboard made of virgin fibres is 40 % stronger than cardboard made of recycled fibres. Therefore, an estimation of the costs and energy-intensiveness of cardboard needs to be drawn up for every single project. The transportation of demolished cardboard structures to a recycling yard may be more expensive than the production of new cardboard from different source materials.

The demolition of buildings made out of cardboard results in less waste than the demolition of buildings constructed using traditional building materials. On the other hand, the materials needed for the foundations, joints and reinforcement of cardboard structures may have a negative impact on the environment and be a source of waste. Therefore, research will have to be conducted on more sustainable materials complementing cardboard structures.

Materials like glue, coating or resins, used to connect the various elements of cardboard structures or to protect them from water and fire, may cause cardboard elements to be unsuited to recycling. When it comes to the sustainability of paper buildings, this is a decisive factor.

Decisions on the recyclability of the various parts of the building should be taken into account during the design phase. The types of connections and impregnation methods used have a crucial impact on the pro-ecological properties of cardboard used as a building material.

Foundations are the greatest problem from a pro-ecological point of view. Therefore, they should be carefully designed. Solutions may include beer crates (as used at Westborough School), old car tyres filled with earth (as used at Paper Log House), sand bags, earth bags, etc.

When it comes to disassembling the buildings, the connections between the elements are one of the most problematic issues.

Issues concerning production, design, construction, disassembly and dumping or recycling of the materials should be considered at an early stage of the design and development, to ensure the loop is closed.

Cardboard's high level of embodied energy is offset by its thermal performance. The overall lifetime energy costs are low for cardboard buildings, even considering the potentially frequent replacements of building components.

While the technology of natural and biodegradable fire protection methods, waterproofing films, paints and glues are not yet developed to a satisfactory level, the use of cardboard should be restricted to temporary emergency houses, temporary exhibition spaces or indoor objects which require less durability and waterproofing and where the use of such treatments may not be necessary

As for thermal insulation, cardboard performs better than any ordinary material.

Experiences in building with cardboard and research show that cardboard can serve as an alternative construction material, whose use is attractive from an environmental point of view. However, a considerable amount of research is still needed, especially with regard to finding satisfactory solutions in terms of durability, fireproofing and weatherproofing.

Paper and cardboard structures should be promoted as building products. Otherwise cardboard will always be associated with experimental constructions, and it will never lose its image as a low-quality and disposable packaging material. The advantage of cardboard as a building material is the ease with which it can be demolished, disposed of and recycled, compared to traditional materials.

In comparisons of cardboard-core sandwich walls with conventional brick or concrete walls, sandwich walls have clearly proved to be superior in terms of weight, price and U-values. [10]

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