9 Conclusions

§ 9.1 Introduction

This study has demonstrated how paper and its derivatives can be used as a building material and main structural material in design and architecture. The usage of paper in architecture is limited by many factors, including its vulnerability to moisture, humidity and water, creep and the limited variety of products created by the paper industry. However, paper and paper products can be successfully used in several types of architecture and design. The advantages of using paper in architecture are its low price, the fact that it is mass-produced, its ease of recycling and the mechanical properties of the material.

The paper industry's current focus seems to be on packaging materials and new functionalities of paper and cellulose-based materials. Paper will never replace traditional building materials, but it can fulfil a niche demand created by certain designers and architects. It can be used for products such as interior and industrial design, including everyday objects, partition wall systems, furniture, exhibition pavilions, stage sets, venues for temporary events such as trade fairs or major sporting events, medium-lifespan housing (with a lifespan of up to twenty years) for the private and public sectors, public buildings emergency shelters.

This Chapter 8 presents the conclusions of this thesis. First, the research questions and sub-questions are discussed. The research questions are answered in the relevant chapters of the thesis. Chapter 2 presents the some fundamental research on paper, including its history, production, mechanical properties and products produced by the paper industry. Chapters 3 and 4 present the scope of paper usage in design and architecture. Chapter 3 presents the types of paper designs in architecture, while Chapter 4 outlines developments in paper architecture on the basis of sixteen realised structures. The buildings are described in detail, with a particular focus on structural engineering and the paper products used in the various projects.

Chapters 3, 4, 5 and 6 follow a research-by-design approach which includes engineering and prototyping. These chapters present prototypes of paper furniture, pavilions, domes and shelters, made of paper products such as corrugated cardboard, honeycomb panels, paper tubes and U- and L-shaped cardboard profiles. The prototypes in question were built by the author of this thesis and his students and partners. They demonstrate different approaches to the potential use of paper in architecture.

Chapter 7 presents the project of the Transportable Emergency Cardboard House. TECH is the final project encompassing the author's fundamental, material and design research and previous prototypes. There are three generations of TECH, each of which is subsequently improved with regard to its design, structural system and method of impregnation.

Chapter 1 outlined two primary research questions, as well as seven secondary research questions. The answers to these questions can be found in the present chapter.

§ 9.2 Research questions

Primary research question no. 1

What is paper and to what extent can it be used in architecture?

The answer to the above question is given in the first, theoretical part of the thesis. Through a description of the invention of paper and its development, the author shows how paper influenced the development of civilisation. This fundamental research on paper focused on three levels:

- The micro level, which refers to the cellulose fibres that are the fundamental building blocks of paper
- The meso level, which is paper itself and paper products that have the potential to be used as architectural elements and components
- The macro level, which consists of spatial structures and buildings composed of paper-based elements.

The first primary research question can be broken down into four secondary questions regarding the material and its origin, the properties of paper in the context of architectural usage, the current output of the paper industry and its implementation in architecture, and the extent to which paper can be applied in design and architecture.

Sub-question 1.1 – this question is answered in Chapter 2

What is paper, a material known to mankind since 105 AD?

Paper is a material of organic origin. The most commonly used raw materials from which paper is made are deciduous and coniferous trees. However, paper can also be made of other plants, such as straw, hemp, cotton, bamboo, cane and other cellulose-containing materials. Moreover, recycled paper is increasingly used as a source material for new paper.

Paper-making is divided into two phases. The first stage is the preparation of paper pulp, while the second one is the processing of the pulp in paper mills, so as to form sheets of paper.

Pulp consists of small, elongated plant cells that form a compact tissue made of raw material. The pulp used in paper production must be ground into individual fibres. Sheets of paper are produced by using the fibres' ability to form bonds with each other during a process of irrigation, heating and pressing.

Paper is created by a uniform distribution of a slurry containing cellulose fibres across the surface of a screen. The Kraft pulping method is the preferred method to produce strong paper that may be used as an element of architectural structures. Due to its single-fibre properties, the best paper for architectural use is softwood Kraft paper.

Paper was invented in 105 AD by the Chief of the Chinese Imperial Supply Department, Cai Lun, also known as Ts'ai Lung. Afterwards, paper became a popular medium for writing, slowly replacing silk scarves and bamboo boards as media used for messages. Paper was also commonly used as a material for objects for everyday use.

Before paper was introduced and adopted by other parts of the world, other materials were used as information carriers, such as bricks, lead, brass or bronze sheets, pieces of wood, the inside of tree bark, tree leaves, vellum, parchment, stone tables or papyrus.

Although the Chinese kept the technique used to make paper secret, paper appeared in Korea in the sixth century AD and was introduced to Japan in the seventh century AD.

In the eighth century, the art of paper-making spread to the Arab world. The Arabs introduced paper-making techniques to Europe in the twelfth century.

In the centuries that followed, many countries developed paper-producing techniques, but the most significant development took place in Europe between the seventeenth and nineteenth centuries. During those centuries new production techniques were developed, the most notable of which was the first machine to produce paper strips continuously, invented by Louis-Nicolas Robert in 1799. The other major breakthrough in the production of paper was the research conducted on the raw material for paper. The growing demand for paper and the scarcity of raw materials (until the second half of the eighteenth century, mostly rags) resulted in new breakthroughs in the production of paper. New raw material for paper was researched by French physicist and naturalist René Antonie Ferchault de Réaumur, German clergyman Christian Schäffer and German inventor Friedrich Gottlob Keller. After 1840, when Keller managed to gain a pulp from mechanically ground wood, wood (with some added improvements) became the main source of raw material for paper pulp, which resulted in a low-cost but large-scale production of paper.

Although production technologies and the finish of paper have changed and improved over the years, paper has in fact remained remarkably the same over the centuries. It still has the same composition: cellulose fibres bonded in a wet environment, then pressed and dried. Recently, not only the paper-making industry has undergone change, but other industries, such as architecture, electronics and the automotive industry, have also proved receptive to the innovative qualities of paper.

Thanks to a growing awareness of the scarcity of fossil fuels and natural resources, the need to curb CO_2 emissions and the necessity of reducing the ecological burden caused by the use of materials such as plastics, foam, concrete or steel, people are increasingly seeking to find more environmentally friendly solutions, including the circular economy.

Paper and its derivatives can satisfy these needs, although it seems that the golden age of paper is coming to an end. Electronic devices such as smartphones, tablets and e-readers, as well as the growing popularity of electronic media, have taken the place of traditional print media, which has resulted in the paper industry's decline as a producer of information carriers. However, the paper industry may well develop in other directions, e.g. smart packaging. It may provide construction materials in which this renewable and cheap material can make a new start, using and being used alongside new technologies and innovations.

Sub-question 1.2 – this question is answered mainly in Chapter 2

What properties does paper have that make it a usable building material?

In order to answer this question, we must recognise that paper is a non-uniform, fibrous, viscoelastic, plastic, non-linear, anisotropic and hygroscopic material, whose main building component is cellulose.

Cellulose is the most valuable material and main component of the plants used for the production of paper. Pulp is produced by the extraction of cellulose, whose fibrous character forms the basis of paper.

Cellulose is a natural multi-molecular compound, belonging to the polysaccharide group. The macromolecule has a chain structure in which so-called glucose residues are linked by β-glycoside bonds. Together with hemi-cellulose, cellulose forms the skeleton of cells.

Cellulose is a colourless, insoluble fibrous substance with a density of 1.58 g/cm^3. A single cellulose fibre has an elastic modulus of about 130 GP, and its tensile strength is close to 1 GPa.

The basic properties of paper are characterised by weight and density, moisture content, physical characteristics, strength properties, optical properties and other criteria.

The properties of paper that have a significant impact on the extent to which paper can be used as an architectural and structural material are apparent density, mechanical properties and vulnerability to water, fire, microorganisms and animals.

Typical apparent density values range from 0.5 to 0.75 g/cm^3. Since cellulose density is 1.5 g/m^3, this means that 50 percent or more of most types of paper is empty space. This space is occupied by air. Apparent density is one of the most important factors affecting the mechanical, physical and electrical properties of paper.

Paper is a non-uniform material, with respect to the direction of the fibres in a sheet of paper. When paper is formed, cellulose fibres are arranged mainly in two directions: machine direction (MD), which accounts for about 70-80% of the fibres, and cross-machine direction (CD), which makes up approximately 20% of fibres. Furthermore, some fibres may be arranged perpendicular to the direction of the sheet of paper, which is called the Z-direction (ZD).

This arrangement of the fibres is what causes the anisotropic characteristics of paper, with MD resulting in stronger paper than CD. The MC/CD ratio depends on the fibres and the production process used. As a result, it is not possible to set this value as a constant.

The mechanical properties of paper are determined by the properties of the fibres used in paper-making, the bonding between the fibres and their geometrical disposition. The mechanical properties of fibres depend on the geometry and chemical composition of said fibres. The chemical properties of fibres depend on the raw material (fresh or recycled, hardwood or softwood) and pulping method used (e.g. chemical, mechanical, chemo-mechanical, etc.). The Kraft chemical method results in the strongest pulp, i.e. the pulp that is richest in cellulose. In the web-like structure that is paper, single-fibre parameters such as form and surface influence the quality of the bonds between the fibres. These bonds are also affected by the quantity of fibres, fillers and additives. Lastly, the mechanical properties of paper are also determined by the production process (forming, pressing, drying, calendering, etc.). In other words, the properties of paper depend on different factors affecting the material at both the fibre level and the network level.

This also means is that every piece of paper can vary from another, as paper is a web of randomly oriented fibres. Such differences can be even more significant if the various types of paper are not produced from the same raw material, by means of the same method or by the same paper machine.

When subjected to long-term loading, paper is considered an orthotropic, non-linear viscoelastic material. Creep is an increase of strain whose stress level remains constant over time. The creep rate (φcr) varies, depending on the nature of the paper, forces, relative humidity and other factors.

The above information shows that it is not easy to standardise paper and that each pile of paper may be quite different from the one next to it, depending on the source material, production method and other factors.

Paper is vulnerable to water, moisture and air humidity. The hydrogen bonds that are formed between cellulose fibres during the production process can weaken when the moisture content of the material rises. Additionally, the matrix between the cellulosic crystals softens when the moisture content increases. Paper is a hygroscopic material, which means that it can absorb moisture from the atmosphere. When paper gets wet, it deforms and finally turns into pulp again. The moisture content of paper depends on relative humidity and temperature. The highest level of moisture is absorbed in humid and cold conditions.

The optimal moisture content of paper is 5-7%, which is the typical moisture content in standard conditions for paper-product testing, at 21°C and 50% relative humidity (RH). If this moisture level is exceeded, strength is reduced by 10% for every one-percent increase in moisture content. Furthermore, the dimensional stability of paper changes depending on the moisture content. For example, in paper tubes, a one-percent change in the moisture content of the material will cause the length of the tubes to change by 0.12%, and their outside diameter by 0.09%.

Sub-question 1.3 – this question is answered in Chapters 2, 3 and 4

Which paper mass-produced products are suitable for use in architectural structures?

Currently there are many different products made of paper or its derivatives that are used in the building industry. They include products such as laminates, wallpaper, paper tubes used as a stay-in-place formwork, honeycomb boards (which are used as door fillers), etc.

There are five main products, which are mass-produced by the paper industry, which can be used as structural elements in architecture:

- Paperboard
- Paper tubes
- Corrugated cardboard
- Honeycomb panels
- L- and U-shapes

Earlier examples of paper architecture were composed mostly of paper board and corrugated cardboard. Later architects also began to incorporate paper tubes and honeycomb panels into their designs. It is important to note that paper is always combined with other materials, so that its best qualities can be used without having to compensate for its weaknesses. In some cases paper structures are enhanced with other building components. Although architects try to use as much paper as possible in order to make their structures more eco-friendly or cheap, this architectural Puritanism is not always found profitable.

Plate products like corrugated board or honeycomb panels work well as wall or roof elements, whereas paper tubes can be used most efficiently when employed as slender, load-bearing structures. However, plates can also be used as structural elements of a building when they are incorporated with other members. Corrugated cardboard can be used as a load-bearing material. However, when a greater span is required, use of more slender and stiffer elements is recommended. Plate products, when used as wall or as roof elements, can be incorporated into sandwich panels. An external layer of a protective material such as polyethylene, aluminium, impregnated solid boards, fibreboards or plastic foil is an optional solution. Plates can also be altered by means of insulating material, such as polyurethane foam.

Due to the properties of paper products (e.g. creep when an element is subjected to constant loading), it is generally better to use short elements rather than long ones.

An important task during the process of designing paper structures is deciding on the location of the paper-based structural elements within the building. Since paper can be damaged by water, all paper elements that serve as structural parts of a building must be protected from the weather, in the construction stage as well as afterwards, once construction has been completed. In some cases the paper elements can be left untreated. Moreover, paper tubes are round in section, while wall panels are square. Additional wooden battens elements have to attached to the paper tubes to make sure the wall panels can be installed.

Each of the aforementioned products has its own characteristics and properties. Paperboard can be applied as structural elements, such as connections between load-bearing elements or as a finishing, protective layer of a building envelope. Paper tubes and L- and U-shapes made of full board are the best products for use as pillars and beams or linear elements. Corrugated cardboard is at its strongest when used parallel to the direction of the corrugation. It can be used as a bulding element with forces applied parallel to its surface and following the direction of the flute. Honeycomb panels can be used as building elements with the forces applied perpendicular to the surface.

Sub-question 1.4 – this question is answered mainly in Chapter 3

In which fields of design and architecture can paper be used as a building and structural material?

Paper has a history spanning nearly two thousand years. Paper has been used for architectural purposes in Europe for almost five hundred years, in the form of wallpaper, and cardboard and paper have been used as a structural material for more than 150 years. The author researched all these previously realised projects in design and architecture, which resulted in several observations on the specific features of the realised projects. Five functional categories can be defined, whose categorisation depends on the level of complexity, size, material used, budget and lifespan of the project:

- Furniture, interior design, industrial design, arts and crafts and products for everyday use. Generally these products can only be used for about five years.

- Exhibition pavilions, stage sets, objects for temporary events such as trade fairs, exhibitions, major sporting events, etc. Such structures are built for temporary use of up to one year.

- Houses and buildings used by private clients. The maximum lifespan of such buildings is estimated to be about twenty years.

- Public buildings such as schools, universities, sport clubs and galleries. Such structures are built to last a maximum of twenty years.

- Emergency and relief architecture, intended for people who have lost their homes due to poverty, social exclusion, natural disasters and man-made disasters. The lifespan of such buildings is supposed to be five years, but in practice, many of them are used for a longer period of time.

The projects in the aforementioned categories can be realised in different sizes. The S, M, L and XL sizes were established by means of research on projects of art, industrial design, interior design and architecture, realised in the twentieth and twenty-first centuries. The aim of size categorisation is to systematise knowledge of design and architecture made out of paper and cardboard. The size categories not only reflect the physical size of the project (measured in square metres) but also the complexity of the structures, the budget required, the expenses associated with the project and the process of design, research and implementation.

- **Small (S)** – this category encompasses projects with low complexity, composed of a small number of materials. This category includes projects such as furniture and interior design elements, indoor partitions and screens, industrial design and art. Usually, these products, or their elements in case of modular compositions, have a floor area of less than $5m^2$. Products from the Small-size category tend to be mass produced.

- **Medium (M)** – these are structures made out of cardboard, whose complexity level can be managed by a small design team, without any need for advice from a specialist in the field of construction or production. This category encompasses housing structures, major art installations, exhibition pavilions, etc. Such structures are mainly composed of cardboard elements and other materials used for connections between the elements. Special attention needs to be paid to impregnation and the elements' connection with the ground. These projects generally have a floor area of approximately 5-50m^2. The structures can be erected without special equipment or special building equipment like cranes. Projects included in the Medium-size category can be produced in small series or as one-off structures.

- **Large (L)** – these are projects of high complexity – structures made out of prefabricated elements and components assembled on the building site. The buildings in this category have a floor area between 50 and 450m^2. They require a significant financial outlay for material research, experiments and tests, building the prototypes and expert consulting. Their assembly requires specialised construction workers. Cardboard elements are connected by specially designed and produced joints and connectors. In such buildings, other materials are used in addition to cardboard. Generally, these additional materials are timber, steel, plastics and glass. These are one-off projects.

- **Extra Large (XL)** – this category encompasses the most complicated projects in terms of complexity, the composition of the building materials used, technology and production, research and the tests that must be conducted. They require a large financial outlay and special research on materials, durability, strength and experiments. Research and development encompass various fields of science and industry. Projects in this category cover an area greater than 500m^2. They can be realised as one-off projects designed for special occasions, or alternatively, they can be designed to be disassembled and re-assembled in the future. The time required for research and development, design, production and implementation varies depending on the complexity and size of the project.

Despite the above typology, which is based on research on previously realised projects in which paper was used as a main material, the extent to which paper can be used in design and architecture is limited only by the human imagination and creativity.

Sub-question 1.5 – this question is answered mainly in Chapters 3, 4, 6 and 7

To what extent can paper elements be used in architecture with regard to structural system, connections between the elements, connections to the ground and impregnation?

In order to answer this sub-question, research on previously realised products and structures in which paper was used as a main or structural material was required. In addition, the author created seventeen prototypes as part of his research at TU Delft. Other projects, like the Paper Exhibition Pavilion created at Wroclaw University of Science and Technology or Miao Miao Paper Nursery School, broadened the author’s practical knowledge.

There are three different structural systems in which cardboard elements can be used: rod systems, panel/plate systems and shell systems.

1 **Rod structural systems** are mainly composed of long slender elements, such as paper tubes or L- and U-shapes. Such systems are composed of:
   - a **Columns** – in the form of paper tubes or U- and L-shapes (Paper Log House, Paper House)
   - b **Columns-and-beams** – in the form of paper tubes or folded cardboard beams (Miao Miao Paper Nursery School)
   - c **Frames** – rod structural system composed of paper tubes or other cardboard materials with stiff connections between the elements (Hualin Primary School, Cardboard House)
   - d **Arches** – in the form of curved elements or straight connected elements such as paper tubes (Dutch Paper Dome, KUAD Studio)
   - e **Trusses** – rod structural system composed of paper tubes or other cardboard elements (Library of a Poet)
   - f **Space frames** – a structural rod system, truss-like structures in which paper tubes are composed in a geometric 3D pattern (Ring Pass Field Hockey Club).

2 **Panel or plate systems:**
   - a **Flat plates** composed of honeycomb panels (Nemunoki Children's Art Museum)
   - b **Folded plates** composed of honeycomb panels (Westborough Primary School).

3 **Shell systems:**
   - a **Single-layered** triangulated network domes (IJburg Theatre – although this could also be regarded as a single-layered space frame)
   - b **Cylindrical shells** (Apeldoorn Theatre)
   - c **Two-dimensional shell** (Wikkel House)
   - d **Three-dimensional grid shells** (Japanese Pavilion for Expo 2000).

There are six general types of connections between the structural parts of buildings made of paper. They are:

1 **Lamination**
2 **Screw/bolt connections to the joint elements (bracing)**
3 **Post-stressed elements**
4 **Interlocking**
5 **Folding**
6 **Clipping/tiding**

Permanent paper structures are predominantly built on concrete foundations. The overly low foundations of Hualian Primary School, which were actually a leftover from the previous building on the site, resulted in paper tubes being damaged due to capillary action. Alternatives to concrete slabs include heavy components or boxes filled with sand, gravel or rubble. Furthermore, anchoring the building to the ground by means of ground screws or piles can save a lot of work and material and may increase the sustainability of the structure because it hardly touches the ground. Concrete beams or feet placed on the ground are a solution for smaller structures. More temporary buildings can be anchored to the ground with pegs, ropes or by covering the structure with canvas. As paper structures by their very nature are lightweight, the role of the foundations is dual: to keep the structure in its place against wind loads and forces caused by things such as earthquakes and to protect the cardboard structure against moisture from the ground or surface water.

There are several different ways to impregnate paper products:

- **Coating** – a layer of coating is applied to the product after manufacturing in the factory or on the building site. This coating can be applied by soaking, hot-pressing, thermo-fusing, spraying or painting the elements with a repellent. The coating can be natural, bio-based or artificial. Commonly used repellents include bio-polymers, resins, melamine-formaldehyde, urea-formaldehyde, GRP, sulphur polyurethane, polyethylene, gums, sprayed concrete, fibreglass, acrylic varnish, paraffin, wax, boiled linseed oil, copal varnish, polyurethane paints, resin-based paints and sprayed plastics. The coating process makes recycling more difficult since the repellent sinks deep into the structure of the material.

- **Laminating** – lamination allows paper products to be combined with other materials, such as aluminium sheets, film, PVC foil, polyethylene foil, water barrier foil and polyurethane foam. It results in waterproof paper and creates a sandwich composition. The recyclability of such sandwich compositions depends on the type of adhesive and covering material used.

- **Impregnation of the mass** of the material, when substances are added to the pulp during the production process. This method affects the strength of the material. Depending on what type of repellent is used, recyclability may be restricted.

- **Covering** the paper with another type of material, such as shrinking sleeves, canvas or fire- and waterproof paper.

Making paper water-resistant reduces its potential for recycling. It can be assumed that the heavier and more durable the impregnator, the less likely the product is to be recycled.

Sub-question 2.1 – this question is answered mainly in Chapter 5

What is emergency architecture in the context of contemporary humanitarian disasters?

The deteriorating situation of the inhabitants of many countries, especially in the Near East and Africa, has resulted in a growing number of people being forced to leave their homes. UNHCR has reported that the number of forcibly displaced people increased to 65.6 million in the year 2016 as a result of persecution, conflict, violence or human-rights violations. This was an increase of 6.1 million over the 2014 figure. It was also the highest number on record since the end of World War II. This number increased by 23.1 million in the five years since 2011. In addition to the forcibly displaced people, there are many people who have lost their homes due to natural disasters, or who have become homeless for a variety of other reasons. In the year 2015, 364 natural disasters (not including epidemics and insect infestations) were recorded by EM-DAT (the International Disaster Database), which resulted in 22,773 deaths and 98.6 million people affected. Another global problem is homelessness, i.e., a situation in which people or families cannot afford the kind of shelter that is considered adequate and meets the requirements for a minimal existence. This is a problem that occurs not only in poorer countries, but also in so-called developed countries. The OECD database on affordable housing states that 1,777,308 homeless people were reported in OECD countries in 2015.

The right shelter will provide protection against climatic conditions and serve as a transitional home, where people can have their own belongings and room to live, and where they can find emotional security. Shelters must be suitable for different seasons and be culturally and socially appropriate.

The type of relief accommodation to be used depends on the urgency of the demand and the expected lifespan of the accommodation. An emergency shelter is a short-term shelter that provides life-saving support. As it is the most basic type of shelter and can be provided immediately after a disaster, it should not be used for longer than a few days or weeks. Another option is a temporary shelter, which is used for people who are only expected to remain in a certain place for a short period of time – ideally no more than a few weeks. Temporary housing is defined as a place where people can engage in normal daily activities. Such accommodation may come in the form of prefabricated houses. Temporary shelters and temporary houses are so-called ‘transitional shelters’, which means that they are erected for a limited period of time – i.e., just a few months. Such shelters must later be re-used, relocated or recycled. Other types of shelters include progressive shelters and core shelters, which can be turned into permanent houses at the later stage. However, this is only possible if the people know for certain that they can stay in that place.

The minimum size standard for a shelter is 3.5m^2 per person in warm climates and 4.5-5.5m^2 in cold climates. This means that a typical five-member family of refugees who fled Syria will receive a shelter with a floor area of 17.5m^2. The design of the shelter should allow for upgrading or resizing at a later stage if necessary.

The design of the shelter should satisfy certain specific criteria such as structural stability, protection from wind and rain, insulated walls, easy assembly and easy transportation/storage. Furthermore, the shelter should be in line with cultural norms. The design of the shelter should be function-focused and take into consideration the further growth and self-sufficiency of the inhabitants. The materials used to build the shelter should be environmentally friendly as the enormous amount of building waste left afterwards can have a devastating effect on the local environment.

Sub-question 2.2 – this question is answered mainly in Chapters 6 and 7

To what extent can paper be used as a building material for emergency shelters?

Available and low-cost material can be used for serial production of affordable shelters and housing units. These mass-produced and eco-friendly structures will definitely meet the expectations of users with a high level of environmental awareness. However, this is also to say that paper-based structures must be used for commercial applications and that the research conducted for them could also be used for the further development of emergency shelters and houses.

The high insulation properties of paper products form a strong argument in their favour, especially if TECH were to be used to replace tents. It would also reduce the consumption of operating energy and have a positive effect on people’s faith in paper as a building material. The flexible layout of the units can be adapted to suit various housing needs and can also be adapted for commercial use. Thanks to TECH’s readily understood structural system, the likelihood of mistakes made on the construction site would be reduced. Add to this the fact that the system consists of lightweight building elements and components, and you have a shelter that can be erected by unskilled workers. The lightweight elements would also be easy and cheap to transport.

The downside of paper is its vulnerability to water and humidity. Existing solutions, made of plastics or metals, are completely watertight. This vulnerability to water will likely cause users and local authorities to have limited faith in paper. Damage caused by paper architecture users may make the structure even more vulnerable.

The structural properties of paper, which are influenced by the type of pulp used and the way in which the paper is produced, can vary from product to product, and even within one product line. This makes paper a difficult material to standardise, and hence to regulate as a building material.

Due to paper's vulnerability, special impregnation of the building elements is required. Where possible, an impregnation method should be chosen that does not greatly reduce the recyclability of the building.

Sub-question 2.3 – this question is answered mainly in Chapter 7

What kinds of paper products mass-produced by the paper industry are most suitable for use in easy-to-produce, easy-to-transport, low-cost and eco-friendly emergency shelters?

The author analysed four types of products, mass-produced by the paper industry, as part of his research. As mentioned in Chapter 4, which presented case studies of previously realised architectural structures made of paper elements, paper tubes, corrugated cardboard and honeycomb panels are the most popular and most suitable paper products for architectural applications. The author's own contribution to paper-based architecture was his use of cardboard L- and U-shaped beams. These elements are mass produced for packaging purposes. The structural tests conducted by the author demonstrated their high mechanical performance and suitability for paper-based structures.

In paper buildings where the rod system is used, paper tubes are the most commonly used products. Paper tubes are ingenious products due to their geometry and mechanical properties. It is very difficult to produce, say, a timber tube which is hollow inside. Thanks to the geometry of tubes/pipes, they are quite strong and stable even with minimal use of material. Nevertheless, paper tubes, when used as a structural element, are hard to combine with other building components such as walls, because there is a geometrical conflict between the circular shape of the tubes and the linear shape of the walls. Tubes can actually be used as wall elements, as they were in Shigeru Ban's Paper Log House. In such situations, the paper tubes are placed next to each other. However, this solution results in thermal bridges and energy loss at the points where the tubes are connected. Paper tubes are often used as primary structural elements, while the rest of the structure is made out of traditional materials (plastics, metal, timber, etc.). In addition, in many projects in which paper tubes are used as structural elements, the tubes are exposed to natural conditions, which means they are exposed to rain. As a result, they require heavy coating and chemical repellents. They may also require long roof eaves.

Last but not least, most of the previously realised projects described in this dissertation, except for the Paper Log House, are one-off pieces of art, designed and built for one particular situation. This makes them quite expensive, and makes their realisation quite time-consuming.

In the FLe2XARD concept, cardboard T-shapes are used as a primary structural system. These, too, are mass-produced by the paper industry, but they had never been used in architectural applications before. As the T-shape is a perfect shape to combine with another, linear components, T-shaped columns and beams are connected with cardboard wall panels. The system works as a hybrid frame-and-panelling system, with laminated wall and roof panels enhancing the frame structure. The FLe2XARD system was designed and developed to be flexible in terms of functionality and layout. The panels are attached from the outside, and at the same time, they cover the cardboard frame structure against natural conditions like rain or low temperatures. As a result, no heavy coating is needed. It is also possible to replace or change panels even when the house is occupied. The only parts of the structure in which timber is used are the floor component and the joints between the various parts of the frame structure. The rest of the structure (approximately 75% by volume) consists of paper. The wall and roof panels are made out of several layers of laminated cardboard honeycomb panels, which, thanks to the small air pockets between the layers, work perfectly as an insulation material. Therefore, the system can be used in different climatic conditions and temperatures. The panels are coated on the inside with polyethylene film and on the outside with extra PVC foil, which makes them fully recyclable. Lastly, the FLEx2ARD is a structural system that is composed of similar elements: the frame structure and the wall panels are always the same. The roof panels and the rafters may vary in size depending on the basic unit size (small or medium). The system incorporates elements mass-produced by the paper industry, which makes the system significantly more affordable and enables one to mass- or series-produce the houses.

Sub-question 2.4 – this question is answered mainly in Chapter 8

Are building elements and components made out of paper environmentally friendly?

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.

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 may be a source of waste. Therefore, research will have to be conducted on more sustainable materials complementing the cardboard structures.

Materials like glue, coating or resins, which are 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 building, this is a decisive factor.

The foundations of paper-based buildings are the greatest problem from a pro-ecological point of view. Therefore, they should be carefully designed. Solutions may include beer crates, old car tyres filled with earth, sand bags, earth bags, etc.

Issues concerning the production, design, construction, disassembly and dumping or recycling of the materials should be considered at an early stage of the design and development phase, 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.

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 with regard to durability, fireproofing and weatherproofing.

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 sandwich walls with conventional brick or concrete walls, sandwich walls have clearly proved to be superior in terms of weight, price and U-values.

§ 9.3 Further research

This research presented paper in architecture as a primary building material. The author's research focused on paper on three levels: micro, meso and macro. At the micro level, the basic properties of paper and their impact on potential applications of the material in architectural structures were the main topics. The properties of paper are largely determined by the manner in which the pulp and the paper are produced and by the nature of the final product. The meso level is represented by paper products mass-produced by the paper industry. The chosen products were categorised according to their production method and usable properties for architectural applications. The macro level encompasses objects and structures in which paper products were used. The descriptions of the buildings feature certain characteristics such as structural systems, the types of paper products used, the connections between the building elements and components, the connection with the ground and the impregnation methods used. The pro-ecological properties of paper as a building material were presented at the end of this dissertation.

Further research on paper in architecture should focus on several issues that would contribute to the promotion of paper in architecture and would gain the trust of local authorities and potential users of paper architecture. The following areas should be further investigated:

- paper production methods and how to improve the properties of paper
- new paper products that can be applied to architectural structures
- impregnation methods, particularly with biodegradable agents; the methods chosen should protect against humidity, water, fire and microorganisms.

- lamination of paper elements
- recycling of paper elements and components used in architecture
- the properties of paper products in the context of building codes and regulations
- the improvement of properties such as compression and bending strength
- the production of building elements made out of paper

The aforementioned areas should be researched and developed by multi-disciplinary teams, in which chemical engineers and paper-makers should collaborate with designers and structural engineers.