1 Introduction

§ 1.1 1.1. Motivation – the potential of paper in architecture

Paper is a universally found, easily available material of natural origin. It is cheap in production, eco-friendly and easy to recycle and re-use.

Paper has been part of European culture since the twelfth century, when it arrived from the Arab countries through the Iberian Peninsula. Since then it has become a common material, occurring in many different variants and forms: books, greaseproof paper, wallpaper, posters, playing cards, etc. Despite the fact that this 'evolved wood', as Shigeru Ban calls it, is so widely used in other spheres of life, we relatively rarely come across it in the building industry. Paper and cardboard are hardly ever regarded as an independent material or primary construction material.

Actually realised examples of architecture using paper as a main construction material have proved that it is suitable for usage in temporary as well as permanent construction. By exploring the physical structure of paper, as well as its properties and ways to improve these, we can manufacture building components that can be used for the construction of buildings made of paper and its derivatives. Since paper is widely available, affordable and environmentally friendly, it should be recognised as a building material of the future, for the right kinds of buildings with the right kinds of functions.

Take, for instance, the cardboard constructions built by the homeless and refugees. Homeless people use whatever packaging materials they can get hold of in order to construct makeshift shelters in which they are able to survive successive nights in minimal thermal and atmospheric comfort. Paper products can be easily used to create cheap shelters for homeless and roofless people living in European cities, but they have also been used for homeless and roofless people in places such as Japan or Haiti, where thousands of people lost their homes as a result of natural disasters. Conflict zones like Syria or Ukraine need inexpensive residential structures that can serve as

shelters for refugees, but refugees who have made their way to Europe could also be accommodated in individual cardboard shelters. Paper and its derivatives can also be used to build permanent lightweight shelters, suitable for transport by water, land or air, to be used in the most endangered and poorest parts of the world, such as certain countries in Africa, Asia and South America.

Temporary paper buildings can also fulfil the needs of inhabitants of developed countries. 'Neo-nomadism', i.e. the phenomenon whereby people migrate in search of jobs, attractions and opportunities presented by other places, the way nomadic people like the Roma have been doing for centuries, is increasingly common. As a result, more and more mobile solutions are required, in the sphere of architecture as elsewhere. Temporary structures built in specifically designated areas, parts of a city that are temporarily not used, "breaches" created as a result of demolished buildings, districts which are not completely built up or discontinued construction sites can fulfil housing needs, thus becoming part of the state of 'liquid modernity'. [1]

Paper can be used in architecture in many ways. Not only can paper-based materials, such as cardboard, paper tubes and honeycomb panels, be used as building materials for architectural structures, but they can also be used in interior design, furniture-making, industrial design objects and art. With its long tradition, which dates back all the way to the second century AD, paper is a material that is deeply rooted in European culture and particularly in Far Eastern culture. [2]

In order to be able to determine the possible range of the use of paper, people seeking to work with paper must study its structure, basic physical and chemical properties and the ways in which these can be affected. The greatest threat to paper is humidity. Water causes the bonds between the fibre molecules to break, thus turning paper into pulp, which will lose the physical properties essential for load-bearing structures, such as strength and stiffness. Other potentially destructive threats to structures made of paper include fire, fungi and insects. The aforementioned threats can be removed by applying the right type of impregnation to building components made of paper.

The belief that paper can successfully be used as an architectural material, which has been confirmed by successful projects realised all over the world, as well as the author's personal experience with paper as an architectural material, was the main reason why the author of this dissertation took up the subject of testing the properties of paper to be used as a material for building components.

§ 1.2 Background

The author's own fascination with paper as a building material was born during his studies at the Faculty of Architecture of Wroclaw University of Science and Technology (WUST). He developed a great interest in the buildings realised by the Japanese architect Shigeru Ban and in the contrast between the low-tech appearance of paper and the high technology involved in its production. Research on socially engaged design and the further development of the potential of paper in architecture resulted in the author's obtaining his Master's degree from WUST's Faculty of Architecture. His Master's thesis and project, entitled *Architecture of the Excluded: Structure of Homelessness in the City*, were carried out at WUST, under the supervision of Prof. Zbigniew Bac. Both the research and the project revolved around temporary houses for homeless people, who were transitioning between a group shelter and private housing. These 'interchange stations' were designed as temporary cardboard structures located in local communities. The training houses worked as parasites attached to existing structures and buildings for several months (see Section 5.6.6). This Master's project inspired the author to further explore emergency and relief architecture, as well as paper's potential as a building material.

The author was also an active contributor to the 'Humanisation of the Urban Environment' scientific student association. This academic association was established in 2007 by Prof. Zbigniew Bac and the author of this thesis. For the past ten years, Humanisation of the Urban Environment has been involved in several research, design and prototyping projects, including the Paper as a Building Material research and design project established by WUST's Vice-Rector for Student Affairs in 2010-2012, the design and execution of furniture for the *Home(less)ness* exhibition held at Wroclaw Contemporary Museum in 2012, the construction of several pavilions at WUST and higher education trade fairs held in Wroclaw, the construction of the WUST exhibition pavilion marking the seventieth anniversary of the university in 2015 and the construction of the House of Cards. The House of Cards was the winning project of the FUTU Wro contest that was held as part of Wroclaw's European Capital of Culture 2016 festivities, and was realised in Wroclaw as part of the 'Living Unit' section of the 2016 Summer School of Architecture. The aforementioned projects and research were able to be carried out thanks to the support of the Rector and Vice-Rectors as well as the Dean of WUST's Faculty of Architecture.

Subsequent activities were undertaken at Delft University of Technology (TU Delft) in the Netherlands. In 2012 the author of this thesis received a grant for international research. This research was conducted under the supervision of Prof. Mick Eekhout, Chair of Product Development at TU Delft, and Dr Marcel Bilow, also known as 'Dr

Bucky Lab'. A 'Mobility Plus' scientific grant awarded by Poland's Ministry of Science and Higher Education allowed the author to carry out further research at TU Delft and implement seventeen prototypes of paper-based architecture between 2014 and 2016.

During the course of his research, the author successfully applied for an internship with Shigeru Ban Studio at Kyoto University of Art and Design (KUAD), which resulted in a six-month scientific excursion to Japan in 2013. Thanks to financial support from WUST and a 'Young Academic Staff' grant awarded by the EU, the author had the opportunity to conduct research under the supervision of the architect Shigeru Ban, a Professor at KUAD, and his assistant, the architect Yasunori Harano. In addition to this research, the author was a member of the team designing and constructing Miao Miao Nursery School, an emergency relief building whose structure was made of paper. The school was erected in the village of Taiping, in China's Sichuan province, in 2013.

Lastly, the author established a research and design platform for paper in architecture in 2015. This platform, ARCHI-TEKTURA.eu, is a place where one can find information on previously realised projects involving paper as a building material, as well as results of scientific research on paper as a building material.

This dissertation, entitled Paper in Architecture: *Research by design, engineering and prototyping*, was based on research previously conducted at TU Delft's Faculty of Architecture. Between 2003 and 2008, a group called Cardboard in Architecture, under the supervision of Prof. Jan Rots (Chair of the Structural Mechanics department), Prof. Fons Verheijen (Chair of the Architectural Engineering department) and Prof. Mick Eekhout (Chair of the Product Development department), researched cardboard as a building material. The research team consisted of four members and one guest researcher: PhD student Julia Schonwalder ('Mechanical Properties of Cardboard'), PhD student Maria den Boom ('Cardboard Partitioning Walls'), PhD student Taco van Iersel ('Application Designs: Cardboard Cable Duct') and staff member Elise van Dooren (coordination and integration). In 2006 a research fellow from Washington State university, architect Robert Barnstone, was invited to spend his sabbatical in the cardboard research group. The results of the research conducted by the group were presented in a printed publication entitled *Cardboard in Architecture* [3] and in several conference and journal papers.

The works by the architect Shigeru Ban formed another background for this research. In the mid-1980s Shigeru Ban started a new era of paper architecture with the first ever permanent structure made of cardboard, Library of a Poet. Ban co-operated several times with Prof. Mick Eekhout and Octatube B.V. during the assembly of the IJburg Dome Theatre, the Paper Bridge and the Paper Canopy projects. Octatube is a design-

and-build company founded by Eekhout. The architect Nils Eekhout from Octatube designed and built a meeting room for the Ring Pass Field Hockey Club in Delft, the Netherlands. The roof structure of the meeting room is made out of paper tubes connected by space frame connectors.

The author of this thesis was an international visiting researcher at Shigeru Ban Studio at Kyoto University of Art and Design. He took part in the design and realisation of the Paper Nursery School in Ya'an, Sichuan province, China. This school, built from paper, was an emergency kindergarten for victims of an earthquake, built in April 2013.

The author was also inspired by several scientific and academic works on paper in architecture, including but not limited to a PhD thesis by Ozlem Ayan [4] from ETH Zurich, and Master's theses by Branko Sekulić [5] from the Polytechnic University of Catalonia and Mirian Vaccari [6] from Oxford Brooks University.

§ 1.3 Main objectives of the thesis

The main objective of this thesis is research of the properties and potential of mass-produced paper elements, such as paper tubes, honeycomb panels, corrugated cardboard or L- and U-shapes made of full board that can be used as an architectural material in order to fulfil the requirements of contemporary users of architecture. As far as these users are concerned, this thesis focuses mainly on homeless people, refugees and victims of natural and man-made disasters.

For the main objective set this way, auxiliary objectives have been defined:

- fundamental research on paper, a material that has existed since the second century AD
- material research on paper, its production and its properties
- analysis of existing applications of paper in architecture and designs featuring paper as a main building material
- analysis of research and laboratory work undertaken when paper-based components to be used in buildings were constructed

– presentation of the PhD candidate's own research and experiments in projects featuring paper as an architectural material

– tests and experiments on samples of paper components designed by or in association with the author of this thesis

– analysis of the possibility of using paper in the building industry, focusing on its properties, benefits and potential and the risks associated with paper.

The secondary objective of this thesis is to systematise available knowledge as a source of information for designers and engineers interested in the possibility of using paper in architecture.

Drawing on his own experience, on the experiences of architects and contractors and on successfully realised buildings made of paper, the author assumes that constructing a building from paper components is not only possible, but also legitimate in economic, pro-ecological and aesthetic terms.

§ 1.4 Research questions

This thesis asks two primary questions:

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

2 **What is the most suitable way to use paper in emergency architecture?**

In order to answer the primary research questions, some secondary questions were asked, and the answers to these questions are presented in the various chapters of this thesis.

The sub-questions associated with primary question no. 1 are:

- **What is paper, a material known to mankind since 105 AD?**
  This question is answered in Chapter 2.

- **What properties does paper have that make it a usable building material?**
  This question is answered Chapter 2.

- **Which paper mass-produced products are suitable for use in architectural structures?**
  This question is answered in Chapters 2, 3 and 4.

- **In which fields of design and architecture can paper be used as a building and structural material?**
  This question is answered in Chapters 3 and 4.

- **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?**
  This question will be answered in Chapters 3, 4, 6 and 7.

The sub-questions associated with primary research question no. 2 are:

- **What is emergency architecture in the context of contemporary humanitarian disasters?**
  This question is answered in Chapter 5.

- **To what extent can paper be used as a building material for emergency shelters?**
  This question is answered in Chapters 5, 6 and 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?**
  This question is answered in Chapter 7.

- **Are building elements and components made out of paper environmentally friendly?**
  This question is answered in Chapter 8.

§ 1.5 Theses

The theses of this research is the assumption that paper makes a legitimate architectural material on account of its properties, availability, price and environmentally friendly qualities. Paper and cardboard are materials with highly usable properties, although at present, they are not often implemented in interior and industrial design, art or architecture.

The author seeks to prove that paper is a suitable architectural material for the construction of different types of structures, including shelters for refugees, the homeless, the roofless and victims of disasters. Paper buildings may also meet a new demand for temporary dwelling places for people who only stay in places temporarily and are always on the move – so-called modern 'neo-nomads', or inhabitants of what has been called 'liquid modernity'.

Paper structures may serve as furniture, stage sets, pavilions and temporary venues for events like the Olympic Games, trade fairs, exhibitions, etc.

§ 1.6 Research methodology

Examining the potential of paper-based products as architectural materials requires knowledge of architecture, building codes, production and construction, but also of chemistry and the paper industry, particularly with regard to production methods and how to alter and improve the properties of paper. Furthermore, in order to answer the questions concerning the possibility of using paper in architecture for the homeless and the roofless, a researcher must have some knowledge of sociology and psychology.

The following research tools were used during the writing of this PhD thesis:

- Literature research regarding architecture, the physics of paper-making and building, sociology, psychology and other sciences, in order to outline the history of paper-making, and in order to be able to present existing buildings featuring paper as the main architectural material
- Drawing up a model and process of researching the properties of paper as an architectural material

- Analysis of research and measurements conducted by scientific institutes and building companies concerning the properties of paper components used in construction

- Experiments and tests concerning the properties of paper and the ways in which these properties can be affected

- Introduction of results obtained through experiments to newly created architectural and design projects

- Construction of different models, and prototypes. Successful research requires examination through designing and realisation, including the author's own projects, realised within the ARCHI-TEKTURA.eu research and design platform for paper architecture, projects conducted with the Paper as an Architectural Material interdisciplinary research team in cooperation with the Humanisation of the Urban Environment scientific association affiliated with Wroclaw University of Science and Technology's Faculty of Architecture, projects conducted with students at Wroclaw University of Science and Technology's Faculty of Architecture, projects designed and built by Shigeru Ban Studio at Kyoto University of Art and Design, Shigeru Ban Architects and the Voluntary Architects Network and projects realised as part of the Bucky Lab course taught by the author at Delft University of Technology's Faculty of Architecture.

- Methodology for Product Development in Architecture created by Mick Eekhout was used for the development of TECH (Transportable Emergency Cardboard House). [7]

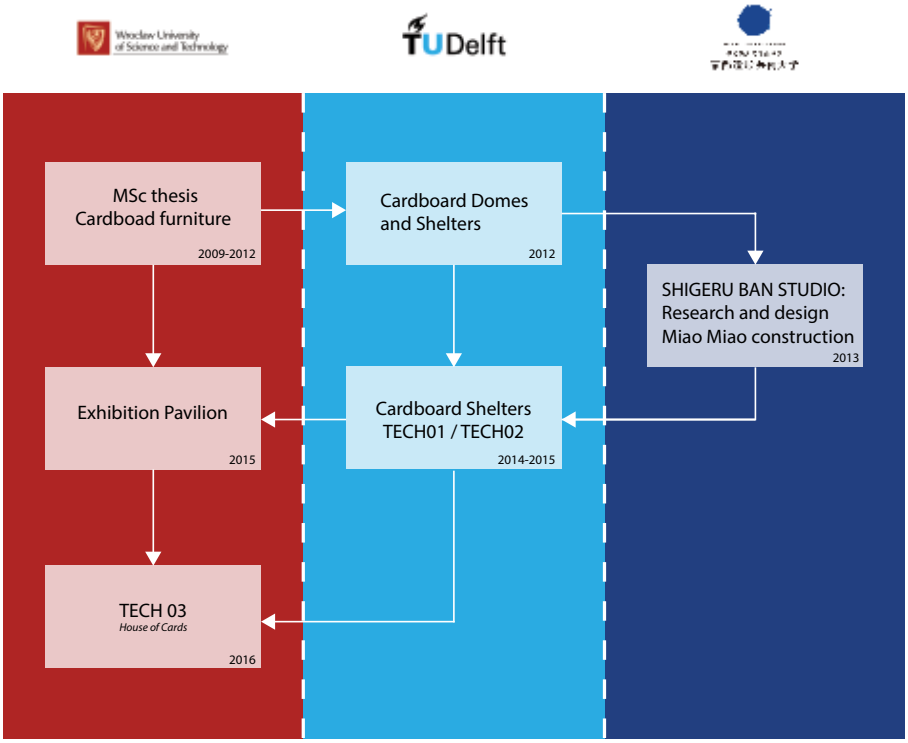

FIGURE 1.1 Schematic representation of the author's research and practical experience

§ 1.7 1.7. Research outline

This dissertation is divided into two main sections.

The first section of the dissertation concerns material and fundamental research as well as case studies of previously realised projects in which paper was used as a main building or structural material.

The second section concerns the author's own research by design engineering and prototyping.

The first section consists of three chapters (Chapters 2-4), and focuses on paper as a building material and possible applications of the material in design and architecture. The properties of the material are considered 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.
  By adopting a multi-level approach, we can learn which properties of paper are essential for building purposes and how they can be modified and improved.

The second section (Chapters 5-7) focuses on design guidelines for emergency shelters and their implementation in the form of prototypes. The author's own experience with research by design and prototyping is showcased in the form of nineteen prototypes of cardboard shelters and domes and three generations of TECH (Transportable Emergency Cardboard House). The final project, called TECH 03, is the most developed housing unit made out of paper-based components.

Brief description of the contents of the following chapters:

Chapter 2: Paper. History, production, properties and products

This chapter presents the history and historical methods of paper-making and provides more information on how paper is produced nowadays and what properties the various paper products have.

The first part of this chapter provides information on the writing materials that preceded paper, such as papyrus, parchment, tapa, etc. It also provides more information on how the Arabs brought the art of paper-making from Asia to Europe and how the paper industry has since developed.

The second part of the chapter presents contemporary paper-making methods. More information on the various types of paper products and their chemical and physical structures is provided in this section. Different grades of paper and their properties are described, categorised by their production processes.

The third part of this chapter provides more information on the paper-based products manufactured by the paper industry. Elements such as paper tubes, corrugated cardboard, honeycomb panels, full board and L- and U-shapes, which are mass produced by the paper industry, are described in terms of usefulness for architectural applications.

Chapter 3: Paper in design and architecture. Typology

Chapter 3 presents how paper can be used to create objects of varying sizes, ranging from small objects for everyday use such as book cases and wallets through interior design objects such as screens, furniture and lamps to large-scale objects such as pavilions and structures for trade fairs, festivals and exhibitions. The objects are categorised by their scale (S,M,L and XL) and level of complexity. The final part of the chapter describes architectural structures made out of cardboard for housing and commercial buildings.

Chapter 4: Paper structures. Case studies

Chapter 4 consists of case studies of paper structures realised in the last 150 years. In the second half of the chapter, seventeen buildings are described in detail, taking into account their structural systems, the materials used to create them, their connections to the ground, their wall and roof compositions and the impregnation methods used. These projects ranging from temporary structures to permanent buildings.

Chapter 5: Emergency and relief architecture. Motivation and guidelines for temporary shelters

Chapter 5 deals with emergency architecture. First different types of people requiring emergency architecture are described, such as forcibly displaced people, asylum seekers, refugees or homeless persons. This chapter is a guideline for emergency architecture.

Chapter 6: Paper Domes and Shelters. Prototypes

Chapter 6 presents the author's own approach to spatial structures made out of paper. The projects realised in the scope of the research-by-design methodology of paper domes and shelters realised as part of the Bucky Lab course taught at TU Delft's Faculty of Architecture represent various structural systems and material application. Over a dozen prototypes were designed and built by students of TU Delft, supervised by the author of this dissertation. The projects accomplished as part of the Bucky Lab course of the Architectural Engineering and Building Technology tracks at TU Delft's Faculty of Architecture and the Built Environment were a series of prototypes that allowed the students to work out and examine different structural, geometrical and material compositions in paper architecture.

Chapter 7: TECH (Transportable Emergency Cardboard House)

Chapter 7 is the final 'real' chapter of the thesis, in which a new solution in relief architecture is proposed. TECH (Transportable Emergency Cardboard House) is a result of the many types of research conducted by the author. Material research showed that elements like U and L-shapes fit into design requirements. Different impregnation techniques examined before were implemented in the prototype of the structure. The research by design helped the author draw up boundary conditions. TECH was designed and further detailed in accordance with the Methodology for Product Development in Architecture. The final result was a prototype of the so-called House of Cards, which was exhibited at the main square in Wroclaw, Poland, and was later transported to the campus of Wroclaw University of Science and Technology for further observations in changing natural conditions.

CHAPTER 8: Paper and cardboard as sustainable materials

Chapter 8 presents the discusson on paper as a building material in the context of energy intensive production and material properties.

CHAPTER 9: Conclusions

The final chapter of the thesis provides conclusions on the research undertaken by the author and answers to the research questions.

Appendix

Appendix contains the description of compression and bending tests conducted on laminated cardboard U-shapes.

References:

1 Bauman, Z., Utopia with no Topos. History of the Human Sciences, 2003. 16(1): p. 11-25.

2 Jackson, P., Folding techniques for designers: from sheet to form. 2011: Laurence King Publishing.

3 Eekhout, M., F. Verheijen, and R. Visser, Cardboard in architecture. 2008, IOS Press: Amsterdam.

4 Ayan, O.z., Cardboard in architectural technology and structural engineering a conceptual approach to cardboard buildings in architecture. 2009, ZürichETH.

5 Sekulić, B., Structural cardboard: feasibility study of cardboard as a long-term structural material in architecture, in Universitat Politècnica de Catalunya. Departament d'Estructures a l'Arquitectura. 2013, Universitat Politècnica de Catalunya.

6 Vaccari, M., Environmental Assessment of Cardboard as a Building Material, in School of Building Environment. 2008, Oxford Brooks University: Oxford. p. 100.

7 Eekhout, M. and ebrary Inc., Methodology for product development in architecture. 2008, IOS Press,: Amsterdam. p. 230 p.