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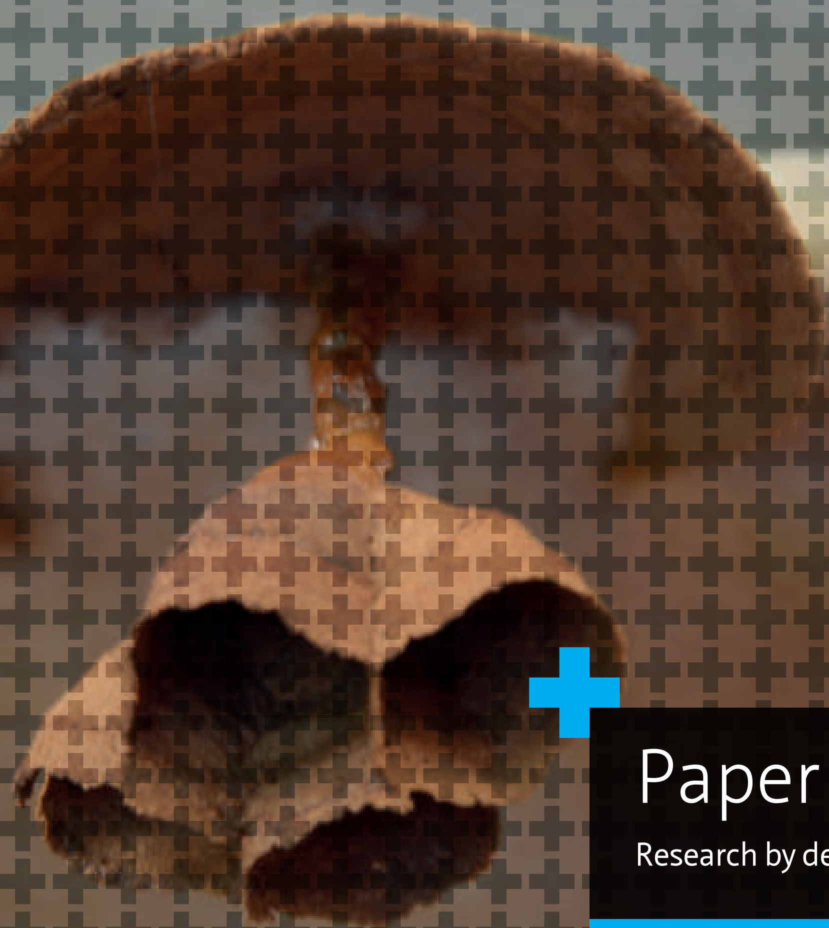

Paper in architecture

Research by design, engineering and prototyping

Jerzy F. Latka

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Research by design, engineering and prototyping

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Architecture and the Built environment

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Cover image: photo by Jerzy Latka, 2013. The picture presents a wasps' nest built on the edge of a corrugated cardboard box. The nest is a tiny structure that could be considered a form of architecture. Wasps and hornets were the first known creators of paper, turning wood fibres into paper-like nests. The discovery of this fact in the eighteenth century radically changed the way in which paper was produced, which resulted in paper becoming a widely available material. Moreover, these particular wasps clearly built their nest on the cardboard because they felt that it was a natural and eco-friendly material. Thus a natural paper nest grew from a factory-produced paper box, which could be regarded as a metaphor for the symbiosis between nature and culture.

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Paper in architecture

Research by design, engineering and prototyping

Proefschrift

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Door

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This dissertation has been approved by the

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to my Parents
(like fibres and water)

Contents

List of tables and figures

Chapter 1

Chapter 2

Chapter 3

Chapter 4

Chapter 5

Chapter 6

Chapter 7

Chapter 8

Appendix

Summary

Paper is a fascinating material that we encounter every day in different variants: tissues, paper towels, packaging material, wall paper or even fillers of doors. Despite radical changes in production technology, the material, which has been known to mankind for almost two thousand years, still has a natural composition, being made up of fibres of plant origin (particularly wood fibres). Thanks to its unique properties, relatively high compression strength and bending stiffness, low production costs and ease of recycling, paper is becoming more and more popular in many types of industry.

Mass-produced paper products such as special paper, paperboard, corrugated cardboard, honeycomb panels, tubes and L- and U-shapes are suitable for use as a building material in the broad sense of these words – i.e., in design and architecture. Objects for everyday use, furniture, interior design elements and partitions are just a few examples of things in which paper can be employed. Temporary events such as festivals, exhibitions or sporting events like the Olympics require structures that only need to last for a limited period of time. When they are demolished after a few days or months, their leftovers can have a significant impact on the local environment.

In the context of growing awareness of environmental threats and the efforts undertaken by local and international organisations and governments to counter these threats, the use of natural materials that can be recycled after their lifespan is becoming increasingly widespread.

Paper and its derivatives fascinate designers and architects, who are always looking for new challenges and trying to meet the market's demands for innovative and pro-ecological solutions.

Being a low-cost and readily available material, paper is suited to the production of emergency shelters for victims of natural and man-made disasters, as well as homeless persons.

In order to gain a better understanding of paper's potential in terms of architecture, its material properties were researched on a micro, meso and macro level. This research of the possible applications of paper in architecture was informed by two main research questions:

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

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

To answer the first research question, fundamental and material research on paper and paper products had to be conducted. The composition of the material, production methods and properties of paper were researched. Then paper products with the potential to be used in architecture were examined. The history of the development of paper and its influence on civilisation helped the author gain a better understanding of the nature of this material, which we encounter in our lives every day. Research on objects for everyday use, furniture, pavilions and architecture realised in the last 150 years allowed the author to distinguish various types of paper design and paper architecture. Analysis of realised buildings in which paper products were used as structural elements and parts of the building envelope resulted in a wide array of possible solutions. Structural systems, types of connections between the various elements, impregnation methods and the functionalities and lifespan of different types of buildings were systematised. The knowledge thus collected allowed the author to conduct a further exploration of paper architecture in the form of designs and prototypes.

To answer the second research question, the analysed case studies were translated into designs and prototypes of emergency shelters.

During the research-by-design, engineering and prototyping phases, more than a dozen prototypes were built. The prototypes differed in terms of structural systems, used materials, connections between structural elements, impregnation methods, functionality and types of building. The three versions of the Transportable Emergency Cardboard House project presented in the final chapter form the author's final answer to the second research question.

Paper will never replace traditional building materials such as timber, concrete, steel, glass or plastic. It can, however, complement them to a significant degree.

Samenvatting

Papier is een fascinerend materiaal dat we elke dag in verschillende vormen tegenkomen: tissues, papieren handdoekjes, verpakkingsmateriaal, behang en zelfs het materiaal waarmee deuren gevuld worden. Ondanks ingrijpende veranderingen in de productietechnologie heeft het materiaal, waarmee de mens al bijna tweeduizend jaar bekend is, nog altijd een natuurlijke samenstelling. Het bestaat nog altijd uit vezels van plantaardige oorsprong (met name houtvezels). Dankzij zijn unieke eigenschappen, relatief hoge druksterkte en buigstijfheid, lage productiekosten en eenvoudige recycling wordt papier steeds populairder in diverse takken van de industrie.

In grote hoeveelheid gefabriceerde papieren producten zoals speciaal papier, karton, golfkarton, honingraatpanelen, kartonnen tubes en L- en U-vormige hoeken zijn geschikt om als bouwmateriaal te worden gebruikt, in de brede zin van het woord – namelijk zowel in design als in architectuur. Voorwerpen die we in ons dagelijks leven gebruiken, meubels, spullen voor onze interieurvormgeving en kamerschermen zijn maar een paar voorbeelden van zaken waarin papier kan worden verwerkt. Tijdelijke evenementen zoals festivals, tentoonstellingen of sporttoernooien zoals de Olympische Spelen hebben gebouwen nodig die maar een beperkte levensduur hoeven te hebben. Als dat soort gebouwen na een paar dagen of maanden afgebroken worden, kan dat een behoorlijke impact hebben op het plaatselijke milieu.

In deze context van een groeiend bewustzijn van bedreigingen voor het milieu en de pogingen die plaatselijke en internationale organisaties en overheden ondernemen om deze bedreigingen tegen te gaan, wordt steeds meer gebruik gemaakt van natuurlijke materialen die na het einde van hun levensduur kunnen worden gerecycled.

Papier en daarvan afgeleide materialen zijn een bron van fascinatie voor ontwerpers en architecten, die altijd op zoek zijn naar nieuwe uitdagingen en altijd proberen het hoofd te bieden aan de vraag van de markt naar innovatieve en milieuvriendelijke producten.

Aangezien het een goedkoop en overal beschikbaar materiaal is, is papier zeer geschikt voor noodopvangsgebouwen voor slachtoffers van natuurlijke en door de mens veroorzaakte rampen, en tevens voor de opvang van daklozen.

Om beter te begrijpen hoe papier potentieel gebruikt zou kunnen worden in de architectuur, werden de eigenschappen van het materiaal onderzocht op drie niveaus: micro, meso en macro. Dit onderzoek naar de mogelijke gebruikswijzen van papier in de architectuur was gestoeld op twee onderzoeksvragen:

Wat is papier en tot op welke hoogte kan het in architectuur worden gebruikt?

Wat is de meest geschikte manier om papier te gebruiken voor de productie van noodopvangsgebouwen?

Om de eerste onderzoeksvraag te beantwoorden, werd er fundamenteel en materiaalonderzoek verricht naar papier en van papier afgeleide producten. Er werd onderzoek gedaan naar de samenstelling van het materiaal, productiemethoden en de eigenschappen van papier. Vervolgens werd er nader gekeken naar papierproducten die potentieel in de architectuur zouden kunnen worden gebruikt. Dankzij de geschiedenis van de ontwikkeling van papier en de invloed van papier op de beschaving kreeg de auteur beter inzicht in de aard van dit materiaal, dat we elke dag om ons heen tegenkomen. Het onderzoek naar alledaagse producten, meubels, paviljoenen en architectuur die de afgelopen 150 jaar tot stand zijn gebracht gaf de auteur de gelegenheid om diverse soorten papieren design and papieren architectuur van elkaar te onderscheiden. Een analyse van daadwerkelijk opgeleverde gebouwen waarin papierproducten zijn gebruikt als structuurelementen en onderdelen van de bouwschil leverde een breed scala aan mogelijke gebruiksmethoden op. Er werd systematisch onderzoek gedaan naar constructiesystemen, verbindingen tussen de diverse soorten elementen, impregnatiemethoden en de functies en levensduur van verschillende soorten gebouwen. Met de kennis die dit opleverde kon de auteur vervolgens nader onderzoek verrichten naar het gebruik van papier in de architectuur, in de vorm van ontwerpen en prototypes.

On de tweede onderzoeksvraag te beantwoorden werden de geanalyseerde casussen vertaald in ontwerpen en prototypes voor noodopvangsgebouwen.

Tijdens de research-by-design-, techniek- en prototypefasen werden er ruim een dozijn prototypes gebouwd. De prototypes verschilden van elkaar qua constructiesysteem, gebruikte materiaalsoorten, verbindingen tussen structuurelementen, impregnatiemethoden, functies en soorten gebouwen. De drie versies van het Transportable Emergency Cardboard House-project die in het proefschrift worden gepresenteerd vormen het antwoord van de auteur op de tweede onderzoeksvraag.

Papier zal nooit traditionele bouwmaterialen zoals hout, beton, staal, glas of plastic vervangen. Het kan echter wel een zeer mooie aanvulling vormen op die materialen.

Streszczenie

Papier jest fascynującym materiałem, z którym spotykamy się codziennie w różnych odmianach: chusteczek, ręczników papierowych, opakowań, tapet czy wypełnienia drzwi. Pomimo znacznych zmian w technologii produkcji, papier jako materiał znany człowiekowi od prawie dwóch tysięcy lat pozostał naturalną kompozycją włókien roślinnych (w szczególności włókien drzewnych). Dzięki jego unikalnym właściwościom, względnie wysokiej wytrzymałości na ściskanie i zginanie, niskim kosztom produkcji oraz łatwości recyklingu, papier staje się coraz popularniejszym materiałem w wielu gałęziach przemysłu.

Masowo produkowane wyroby papiernicze takie jak papiery specjalne, tektura lita, tektura falista, płyty o strukturze plastra miodu, tuleje oraz L- i U-kształtowniki nadają się do użycia jako tworzywo w szeroko pojętym projektowaniu i architekturze. Obiekty codziennego użytku, meble, elementy wyposażenia wnętrz, przegrody przestrzenne to tylko niektóre z przykładów, w których można zastosować papier. Tymczasowe wydarzenia, festiwale, wystawy czy imprezy sportowe takie jak olimpiady wymagają stworzenia konstrukcji, które będą użytkowane przez krótki okres. Konstrukcje te po zakończeniu danego wydarzenia, są rozbierane a pozostałe odpady budowlane mają nierzadko negatywny wpływ na środowisko naturalne.

W kontekście rosnącej świadomości zagrożeń środowiska oraz wzmożonych wysiłków podejmowanych przez lokalne i międzynarodowe organizacje i rządy narodowe w celu przeciwdziałania tym zagrożeniom, wykorzystanie naturalnych materiałów, które po okresie użytkowania mogą zostać poddane recyklingowi staje się coraz powszechniejsze.

Papier i jego pochodne fascynują projektantów i architektów, którzy szukają nowych wyzwań a także starają się sprostać zapotrzebowaniom rynku na innowacyjne i proekologiczne rozwiązania.

Papier, jako niedrogi i powszechnie dostępny materiał nadaje się do produkcji schronień pomocowych dla ofiar katastrof naturalnych, działań wojennych lub osób bezdomnych.

W celu lepszego zrozumienia możliwości zastosowania papieru jako tworzywa architektonicznego, zbadane zostały jego właściwości na poziomie mikro, meso i makro.

Niniejsza praca, której celem było zbadanie możliwości zastosowania papieru w architekturze oparta została o dwa główne pytania badawcze:

Czym jest papier i w jakim zakresie może zostać zastosowany w architekturze ?

Jakie jest najlepszy sposób zastosowania papieru w architekturze pomocowej ?

Aby odpowiedzieć na pierwsze pytanie, przeprowadzone zostały badania podstawowe i badania materiałowe nad papierem i produktami papierniczymi. Przeprowadzono badania nad budową materiału, jego właściwościami oraz metodami produkcji. Następnie przestudiowane zostały wyroby papiernicze posiadające potencjał do zastosowania w architekturze. Historia papiernictwa i jego rozwoju a także wpływ papieru na rozwój cywilizacji pozwolił autorowi na lepsze zrozumienie materiału z którym spotykamy się na co dzień.

Przeprowadzone badania nad formami przemysłowymi, meblami, pawilonami oraz konstrukcjami architektonicznymi wykonanymi w ostatnich 150-ciu latach pozwoliły na stworzenie typologii dizajnu i architektury papierowej. Analiza zrealizowanych obiektów, w których produkty papiernicze zostały zastosowane jako elementy konstrukcyjne oraz przegrody budowlane zaowocowała szeroką gamą możliwych rozwiązań. Przygotowano systematykę rozwiązań konstrukcyjnych, rodzajów połączeń pomiędzy elementami budowlanymi, sposobów impregnacji, typów funkcjonalnych oraz żywotności konstrukcji papierowych. Zgromadzona wiedza pozwoliła autorowi na przeprowadzenie dalszych, praktycznych badań nad architekturą papierową w postaci projektów i prototypów.

Aby odpowiedzieć na drugie pytanie badawcze, przeanalizowane rozwiązania z zakresu architektury papierowej zostały wykorzystane w celu stworzenia serii prototypów architektury pomocowej.

Podczas fazy badań przez projektowanie, inżynierię oraz prototypowanie zrealizowanych zostało kilkanaście prototypów. Prototypy te różniły się pod względem systemu konstrukcyjnego, zastosowanego materiału, połączeń między elementami konstrukcyjnymi, metodami impregnacji oraz funkcji. Trzy wersje projektu Transportable Emergency Cardboard House zaprezentowane w ostatnim rozdziale niniejszej pracy stanowią odpowiedź autora na drugie pytanie badawcze.

Papier nigdy nie zastąpi tradycyjnych materiałów budowlanych takich jak drewno, beton, stal, szkło czy plastik. Niemniej, może on z powodzeniem je uzupełnić.

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

TOC

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]

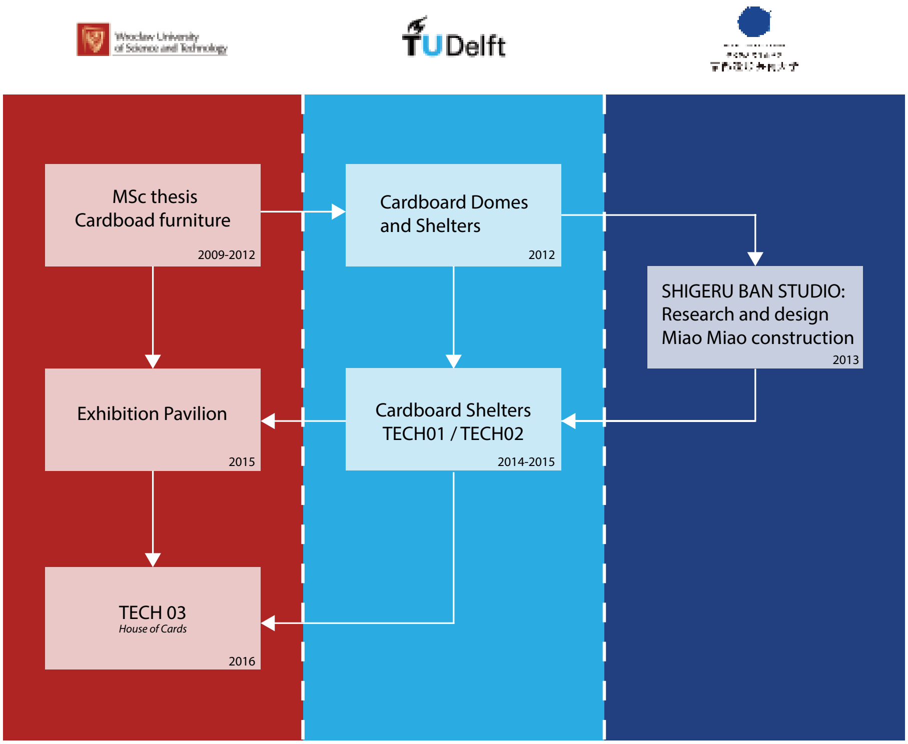

FIGURE 1.1 Schematic representation of the author's research and practical experience

§ 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.

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2 Paper. History, production, properties and products

A tree is a slow explosion of a seed

Bruno Munari, 'Drawing a tree' [1]

§ 2.1 Introduction

Paper is a material we know from our day-to-day lives because it is used in newspapers, tissues, packaging, etc. Its web-like structure consists of wood fibres and can be visualised by comparing it to the cooking of a portion of spaghetti that is later served onto a plate. [2]

Paper is often associated with traditional materials and production technologies. Brought to life in the second century AD, [3, 4] paper has had a significant role in the history of civilisations, from the Chinese empire through the Guttenberg era up to the current 'digital age'. It has primarily been used as an information carrier and packaging material. However, the architectural applications of paper have been known since the eighth century AD. [5]

Although production technologies and the finish of paper have changed and improved over the years, paper has in fact remained remarkably the same through 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, like architecture, electronics, the automotive industry and others, are also receptive to the innovative qualities of paper.

Growing awareness of the scarceness 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 is encouraging people to find more environmentally friendly solutions, including the circular economy. [6]

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 the producer of information carriers. However, the paper industry can develop in other directions, e.g. smart packaging, the provision of energy and construction materials, where this renewable and cheap material can make a new start, using and being used along with new technologies and innovations. [6]

Sustainable development was first described in the Agenda21 document in 1992 and its appendices, which state that the most important challenges for global policy are *improving people's lives and conserving our natural resources in a world that is growing in population, with ever-increasing demands for food, water, shelter, sanitation, energy, health services and economic security*. [7] Moreover, the European Parliament and the Council of the European Union ordered in Directive 2008/98/EC that by 2020, the weight amount of recycled or re-used construction waste must be increased to a minimum of 70%. [8]

These challenges can be addressed by renewable resources – reusable, recyclable, available and affordable materials, among other things. One of these renewable resources is paper.

§ 2.2 Definitions

Quite often the meanings of paper and paper-based products (including cardboard) are confused. To help us get a better understanding of what is paper and what the differences are between paper and other products of the paper industry, the definitions according to the NEN-ISO 4046 1-5 norm [9] are provided below:

- **Paper** *is a generic term for a range of materials in the form of a coherent sheet or web. In the generic sense, the term of "paper" may be used to describe both paper and board. The primary distinction between paper and board is normally based upon thickness or grammage.*

- **Paperboard** *(also board) is a generic term applied to certain types of paper frequently characterized by their relatively high rigidity*

- **Carton board** *(also folding boxboard) is board intended for manufacture of cartons having good scoring and folding properties*

- **Chipboard** *is a board commonly of low grade, made on a continuous machine from a waste paper*

- **Corrugated fiberboard** *is a board consisting of one or more sheets of fluted paper glued to a flat sheet of board or between several sheets*

- **Solid board** *is a board comprising a single furnish layer (layer of paper or board consisting of one or several plies of the same composition)*

- **Solid fiberboard** *is a board which may be pasted (layered) or unpasted often incorporating a lining of Kraft or other strong furnish intended and suitable for the manufacture of packaging and drums. Solid fiberboard generally has a grammage above 600 g/*m^2.

The above definitions show that paper and board or cardboard are in fact the same type of material, and the difference lies in the thickness or grammage (basis weight).

Christopher Biermann in his immense work entiteled *Handbook of pulping and papermaking* (1996) describes paper as: *pliable material used for writing, packaging, and a variety of specialized purposes. Paper consist of a web of pulp (normally from wood or other vegetable fiber), usually formed from an aqueous slurry on a wire or screen, and held together by hydrogen bonding. Paper may also contain a variety of additives and fillers.* [4]

Several distinctions exist between paper and board or cardboard, depending on the country, industry or traditions. There is no clear division between types of paper-based products. For example, Branko Sekulić (2013) [10] states that paper heavier than 150 g/m^2 is normally called paperboard, and that paper heavier than 500 g/m^2 is called board. On the other hand, the CEPI (Confederation of European Paper Industry) in the *Pulp and Paper Industry Definitions and Concepts* document informs readers that *The paper and paperboard category is an aggregate category. In the production and trade statistics, it represents the sum of graphic papers; sanitary and household papers; packaging materials and other paper and paperboard. It excludes manufactured paper products such as boxes, cartons, books and magazines, etc.* [11] In her PhD dissertation entitled *Cardboard in Architectural Technology and Structural Engineering: A Conceptual Approach to Cardboard Buildings in Architecture* (2009), Onzelm Ayan from ETH Zurich states that paper with a density greater than 200 g/m^3 is generally considered to be cardboard. [12] Almut Pohl in her thesis *Strengthened*

Corrugated Paper Honeycomb for Application in Structural Elements (2009) informs that the grammage of paper used for structural purposes is in the range of 80 g/m² to over 300 g/m². [13] Stefan Jakucewicz (2014) distinguishes paper products according to their grammage and construction, with paper being a single-layered product and cardboard a multi-layered one. Jakucewicz refers to the norm ISO 4046:1978, in which a grammage of 225 g/m² is considered to be the boundary between paper and cardboard. However, ISO 4046:1978 was cancelled and replaced with ISO 4046-3:2002, in which this boundary was removed, and paper was defined as a thin paper product with low grammage and cardboard as a thick product with high grammage. [14] However, some materials with a grammage lower than 225g/m², which are used for the production of boxes or corrugated fibreboard, are called cardboard, while some products with a grammage higher than 225g/m², such as drawing or absorbent paper, are called paper.

The above definitions show that there is not one clear distinction between paper and cardboard. It depends on a country's national traditions, common names used by the industry, norms and other documents.

To simplify the distinctions between different types of paper products, it can be assumed here that the differences in grammage between paper and cardboard are as follows:

- **Paper** is a material with a grammage lower than or equal to 225 g/m²
- **Cardboard** is a material with a grammage higher than 225 g/m²

In multi-layered materials (i.e., corrugated board) this boundary is equal to 160 g/m²

With this matter it can be assumed that:

Cardboard is a commonly used term that is associated with thick paperboard or corrugated board. However, in the paper industry, the word 'cardboard' refers to paper board, solid board and corrugated board. In this dissertation the term 'cardboard' will be used for heavy-duty paper, sometimes with additional qualifications, such as corrugated, solid (board), solid fibreboard, chipboard, etc. whose grammage is higher than 225 g/m² for single-layered material and higher than 160 g/m² for multi-layered materials.

Paper based material or paper products is a broad definition of products whose main ingredient is cellulose (mainly wood) fibres.

There are many different grades of paper, board and paper-based products, which will be discussed below, in Section 2.6.9 of this chapter.

§ 2.3 The history of paper production

The 'official' year of the invention of paper is 105 AD. However, paper is likely to have been invented before, and definitely certain species of wasps and hornets had been manufacturing paper and even cardboard ages before man (see Fig. 2.1.). [15] The 'official' birth year of paper is the year in which paper was introduced to Emperor He of the Han Dynasty by the Chief of the Imperial Supply Department, Cai Lun, also know as Ts'ai Lung. [16] Afterwards, paper became a popular medium for writing, slowly replacing silk scarves and bamboo boards as media for messages. As Kiyofusa Narita reports in his book A Life of Ts'ai Lung and Japanese Paper Making (1980), the oldest samples of paper made of flax fibres were found in China by an English explorer, Aurel Stein, in 1907 and have been dated back to the years 65-56 BC. [16] Further evidence that paper existed before 105 AD was the first systematic Chinese dictionary, completed in 69 AD, in which paper had an entry. The legend says that a certain Han Xin, who served at the Court of Emperor Gaozu (247-195 BC), during his youth helped a washerwoman bleach silk floss. Silk floss was cleaned in the water by being beaten on a mat. The broken fibres sneaked through the longer ones and formed a layer on the mat. When such a layer dried, it would become very much like a piece of paper. So the legend followed the logic. [17] On the other hand, there are researchers, among them Jozef Dabrowski (1991), who argue that the product made before Cai Lung was not paper but tapa. [3] Tapa is a material that was used as an information carrier before the invention of paper (see Fig. 2.7). Tapa was obtained by sopping and boiling mulberry tree bark in a lye. Strips of the bark were crushed and beaten with hard tools, then dried. Paper is obtained by a uniform distribution of a slurry containing cellulose fibre on the surface of a screen. A comparison of the structure of paper and tapa will show up differences in the structure of both materials. Tapa consists of strips of material (not pulp), while paper consists of cellulose fibres connected with each other. Despite the differences between both materials, there is no doubt that paper derives from tapa, and the invention of paper-making was closely related to the techniques used to produce tapa.

FIGURE 2.1 Paper nest built on corrugated cardboard

Nevertheless, it is Cai Lun who is recognised by history as the person who gave humankind paper. Cai Lun was asked by the emperor to rearrange the imperial library which consisted of a large number of books made of wooden boards, which were used as a writing material at the time. In order to find handier and lighter material, Cai Lun began experimenting with the bark of mulberry trees, bamboo, grass, hemp, scraps of silk fibres, old fishnets and the bark of *kaji* trees instead of silk floss. The pulped fibres were mixed with some mucilaginous substance in a water solution. Then the material was screened, drained and dried. Although the processes, machinery and technology have changed over the centuries, paper is still made the same way it was then. [16, 17] When paper was invented, its production method was initially kept secret. As a lightweight and relatively cheap material produced out of tree bark, rags and later fishing nets, paper replaced heavy bamboo boards and expensive silk as the preferred material on which to write.

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 (see Fig. 2.3), the inside of tree bark, tree leaves, vellum, parchment, stone tables (see Fig. 2.2) or papyrus (see Fig. 2.4).

FIGURE 2.2 Roseta stone, 196 B.C. – replica

FIGURE 2.3 Wooden slats 27 AD – replica

In China, before the era of paper, rice paper, bamboo boards and the aforementioned tapa were the most popular writing materials. So-called 'rice paper' is actually not paper, nor is it made of rice. The material is produced by carefully cutting the pith of the kung-shu plant. Whereas paper is made of cellulose fibres, rice paper is made of the parenchyma of the plant. It is for this reason that rice paper lacks the strength of conventional paper. [2] . Papyrus, after which paper is named, was the most superior writing surface until the invention of paper. Developed by the Egyptians, papyrus was made of reed leaves that were placed in a row. Then the next row was placed on top of the previous one in the transverse direction. Both layers were pounded together and dried (see Fig. 2.4). During the pounding, the cellulose cells were merged by the formation of numerous hydrogen bonds. Papyrus was widely used as a writing material in Egypt and the Arabic World since 3000 BC. In Central America in the pre-Columbian age, amate was used instead of paper. Amate was produced similarly to tapa (see Fig. 2.5).

FIGURE 2.4 Papyrus

FIGURE 2.5 Amate

FIGURE 2.6 Hemp paper – produced in China, 202 BC-8 AD – replica

FIGURE 2.7 Tapa cloth made in Hawaii

FIGURE 2.8 Parchment sheet with hand-written music, approx, seventeenth century

Prior to the discovery of paper, parchment and vellum (durable, lightweight materials made from the skin of calves, sheep or goats) were the most popular writing materials used in Europe (see Fig. 2.8). Europeans had been using animal hides as a writing material since the second century AD. The name 'parchment' is derived from the Persian city of Pergamon, whose sheets of parchment were known to be of very high quality. [4, 15]

§ 2.3.1 Paper in China

One of the main reasons why paper was used in ancient China was to spread the religious ideas of Buddhism, Taoism and Confucianism. Paper was also used in burial ceremonies as a representation of material goods that were buried with the deceased. In addition to religious purposes, paper was also used for the creation of money. Paper money was first used in China back to 812 AD. In the year 868 AD, the first known Chinese printed book was produced: the Diamond Sutra. In 875 AD toilet paper was first reported by travellers, and in 969 AD the existence of paper playing cards was reported. [15, 18]

Early examples of Chinese paper were made out of hemp, jute, flax, ramie, rattan, paper mulberry (kozo), mulberry and bamboo fibres (see Fig. 2.6). The production process took several days. First, different plants were soaked in water, allowing the bark to be stripped and the cellulose fibres to be released and separated from the lignin. Then selected layers of bark were soaked in a solution of water and wood ashes (potash) and beaten with a mallet. This operation allowed paper makers to separate the cellulose fibres from the lignin. The cellulose pulp thus obtained was poured onto a woven mould or sieve which lay in the water. The paper maker then shook the sieve in order to spread the cellulose fibres evenly. Afterwards the mould would be left outside in the sun to dry.

§ 2.3.2 Paper in Japan

Although the Chinese kept the technique used to make paper secret, paper appeared in Korea in the fourth century AD and was introduced to Japan by a Korean Buddhist monk named Donchó in 610 AD. [16] Since then, the Japanese have created their own way to produce paper. Their paper is called *washi* (*wa* means 'Japanese' and *shi* means 'paper'). The main ingredients of Japanese paper are the bark of the *kozo* plant, *gampi* tree and *mitsumata* shrub. However, other fibres, such as bamboo, hemp, rice and wheat, can be used, as well.

The *washi*-paper-making technique involves steaming plant stems, stripping them while still hot, cleaning the bark, cooking it in alkali and gently beating it in order to lengthen the fibres. The fibres are collected from a solution of water and mucilage of *aoi tororo*, a hibiscus genus plant, by waving the screen previously dipped in the solution. The mucilage minimises entanglement of the fibres.

There are two ways to produce traditional Japanese paper. The first method is *tame-zuki*, imported from ancient China. It involves dipping a screen in a solution of paper ingredients just once and then, after removing it from the solution, shaking the frame back and forth, and from left to right, to make sure the fibres face the right direction.

The second technique, called *nagashi-zuki*, involves scooping the fibres from the solution with a bamboo-netted frame screen, shaking it back and forth and sideways to get the desired pattern of fibres facing two ways. This motion is repeated several times in order to obtain a thicker and stronger sheet of paper. The fibres align in the direction of the waving – in other words, at right angles to each other (see Fig 2.9 – 2.13).

FIGURE 2.9 stripping plants for traditional production of *washi* paper in Echizen, Japan

FIGURE 2.10 beaten bark

FIGURE 2.11 waving the screen previously dipped in the solution (*tame – zuki* technique)

FIGURE 2.12 a wet sheet of paper on a bamboo screen

High-quality paper made of hemp and the *kozo* plant was used for the oldest known printed piece of paper, which contains *dharani*, Buddhist charms from about 770 AD, i.e., some 680 years before Johannes Gutenberg invented the printing press. Millions of *dharani* were printed on sheets measuring 6x45cm. They were placed in small (10x13.5cm) pagodas and dedicated to Ten Major Temples, with the aim of bringing about global peace (see Fig. 2.14).

FIGURE 2.13 Placing the Washi paper sheets on the stock

FIGURE 2.14 Small pagodas and Dharani

§ 2.3.3 Paper in the Arabic World

The Arabs learnt the technique of paper-making from the Chinese after conquering the city of Samarkand in 712. Several Chinese paper-making workshops had been established in Samarkand earlier. [14] Some sources (Goedvriend 1988, Scott et al.

1995) indicate that the art of paper-making was acquired by the Arabs forty years later, after the battle of Talas River, in which the Arabs fought the Chinese and won. Some Chinese paper-makers were imprisoned and sent to Samarkand. [17, 18] Afterwards, the secret of paper-making spread quite fast in the Islamic world. The most important role paper played at the time was to distribute verses of the Koran to believers. Paper replaced papyrus, which was heavier and harder to manufacture. The Arabs also improved the pulping process by inventing mechanised pulp-making involving water mills. The ingredients now no longer had to be manually beaten into a pulp. [17]

§ 2.3.4 Paper in Europe

Knowledge of paper-making came to Europe along with the Arab expansion on the Iberian peninsula. The first paper-making workshop was operating in the year 1144 in the city of Xativa, which is recognised as one of the first European paper producer. [6, 14] The Arabs also established paper production centres in the Apennine peninsula, in Amalfi and Fabriano, which resulted in a new European technology of paper production that involved the use of screw-press machines and gelatine sizing. Soon after that, paper production commenced in other countries. A paper mill was operating in Troyes, France, in 1348. By 1390 there was a paper mill on the outskirts of Nuremberg, Germany. Around 1400 the first paper mill was operating in the southern Netherlands. By 1432 Switzerland was producing paper, by 1491 Poland was doing the same, and England followed in 1495. Paper was produced in Russia by the year 1576, and in the USA by 1690. [14, 18]

When paper appeared in Europe in the twelfth century, parchment and vellum were still the most commonly used writing materials. They were valuable and reliable materials used as information carriers. It took paper several centuries to gain the people's trust. For example, the first printed books in Europe, Gutenberg's Bible, were printed between 1452 and 1455 on both vellum (45 copies) and paper (135 copies). [15]

The European technique of paper-making differed from the techniques used in China, Japan and the Arab world. Instead of the wind-up screens used in Asia, European paper-makers used moulds with copper or brass wires woven together with gaps in between. Because these wires were fastened to the mould, it was not possible to roll them in order to detach the sheet of paper. In Europe woollen felts were used to transfer the paper from the mould and to create stacks of alternating sheets of paper and felts. Such stacks were pressed in screw-press machines in order to get rid of excess water, then dried by being suspended. European paper-makers, like their

Arab counterparts, used water power. Water mills were used to pulp the raw material, which consisted of linen rags and hemp. In addition to this mechanical pulping, rotting raw material was used during the pulping process. However, this process took approximately fourteen days, so it was time-consuming.

Considerable progress in pulping was made in the province of Zeeland in the northern Netherlands, where wind mills were used for pulping. In the 1660s or early 1670s the Hollander beating machine was invented in the Netherlands. Instead of wooden beats, the Hollander Beater used steel blades that cut the raw material, which resulted in a faster pulping process, which did not require fermentation first. As a result, paper-making became cheaper and faster and the Netherlands soon began exporting paper. [4, 14]

A growing demand for paper and the scarcity of raw materials (until the second half of the eighteenth century, the main ingredient was rags) led to new breakthroughs in paper production. New raw material for paper was researched by people such as French physicist and naturalist René Antonie Ferchault de Réaumur, German clergyman Christian Schäffer and German inventor Friedrich Gottlob Keller.

In 1719 de Réaumur presented to the French Academy of Science a tractate in which he noted that wasps and hornets produced thin and delicate paper from which they built their nests. Wood fibres were the source material for that paper. De Réaumur suggested that if wasps and hornets could produce a paper from wood, humankind should also be able to do so. Schäffer, who experimented with different source materials for paper production, ranging from seeds of poplar trees and tulip leaves to cotton grass and potatoes, also paid attention to wasps' nests. Schäffer concluded in his books (1765-1772) that paper can be made out of any plant, and that the different characteristics of plant structure would result in different paper qualities. [15] In 1840 Keller managed to obtain pulp from mechanically grinded wood. [14] After that, and following a few more improvements, wood became the main source of raw material for paper pulp, resulting in low-cost paper-making on a large scale.

In 1799 Frenchman Louis-Nicolas Robert patented a paper-making machine that produced continuous strips of paper. [4] Robert's machine consisted of a continuous perforated sieve, driven and supported by two rollers. The mechanism was installed over an oval vat. By turning the crank, the sieve was moved at a speed of 5m/min, and the use of vanes allowed the fibre stock to be put on a belt (see Fig. 2.15). Then water was drained through the fibres and the small holes in the belt. Sheets of moist fibres created in this way were passed over a felt-covered roller, then dried. The efficiency of Robert's machine was equal to reaping paper from five vats. Improvements to Robert's machine were funded by Henry and Sealy Fourdrinier and developed by Bryan Donkin, who in 1804 built the first practical paper machine, which was in operation at Two Waters Mill, Hertz, England. Since that time, the Fourdrinier machine has become the basis for many modern paper machines (see Fig. 2.16). [14, 18]

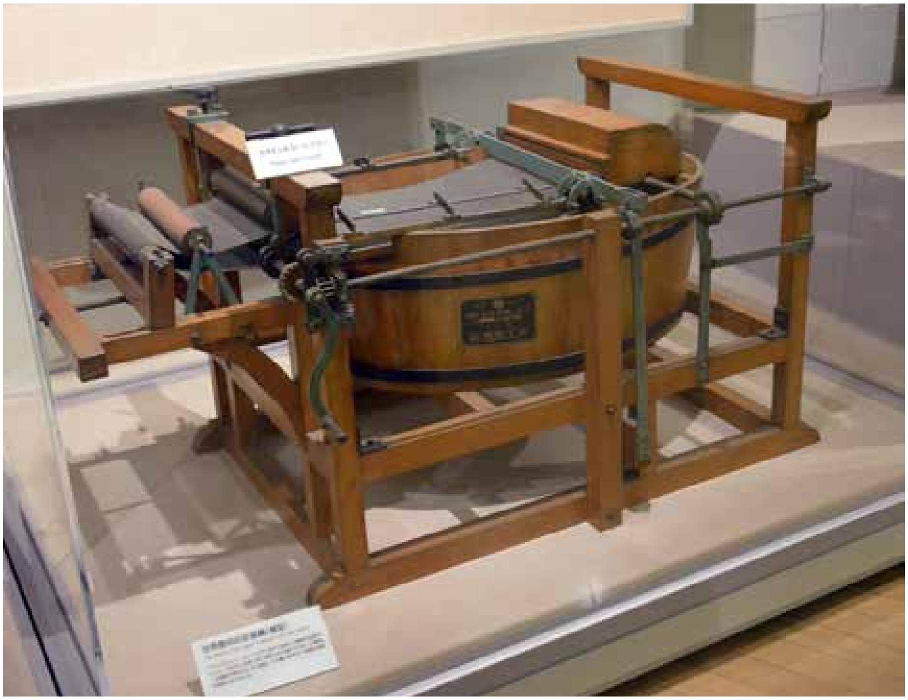

FIGURE 2.15 Model of Louis-Nicolas Robert's paper machine

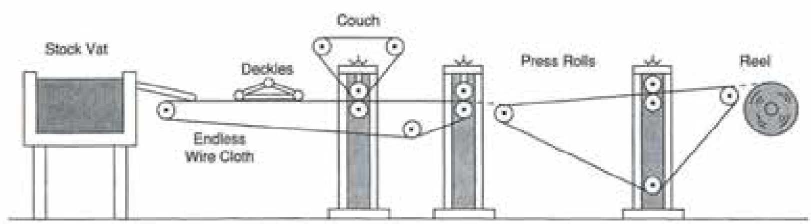

FIGURE 2.16 Diagram of Bryan Donkin's paper machine, 1804

A parallel invention to Robert's machine was a cylinder machine constructed by John Dickinson in 1809. In 1817 Dickinson created a machine with two cylinders, which produced cardboard made of two layers that were combined by wet press. In the same year Dickinson first mentioned a cylinder machine with steam-heated drying cylinders. [4, 14]

In 1881 the American company Thomson & Norris produced the first single-wall corrugated board. [14]

The inventions of the eighteenth and nineteenth centuries concerning raw materials and the production of paper and cardboard resulted in a revolution in the paper industry, which in turn led to mass and cost-effective production of paper products, and further development of the industry. And most importantly, they made paper a widely available material.

Further developments in the twentieth and twenty-first centuries involved chemicals being used in the pulping process and the invention of modern automated machines. In 2010 the German company Voith built the biggest paper machine in the world. It is 600m long and produces paper in rolls that are 11.8m wide at a speed of 1,700m/min, with a maximum efficiency of 4,537 t/24h. Currently there are machines that produce paper rolls with a width of 12.5m at a speed of 2,000m/min, which is four hundred times faster than the first paper machine invented by Louis-Nicolas Robert see Fig. 2.17). [14]

FIGURE 2.17 Modern paper machine, Arctic Paper, Kostrzyn upon Odra, Poland, 2011

Now, in the early twenty-first century, the golden era of paper-making may be about to end. According to statistics provided by CEPI (the Confederation of European Paper Industries), Europe's paper production capacity decreased by 12 percent in the years 2005-2013. Pulp mass production decreased by 10 percent and the production of paper and cardboard by 7%. [19] Due to the advent of modern media such as tablets, computers and other digital file readers, there is less and less need for printing paper. However, the demand for packaging materials is increasing. Paper manufacturers are looking for new business avenues that can offset the reduced demand for traditional paper. One of these new business avenues is the production of new types of paper and cardboard packaging elements such as honeycomb panels, paper tubes, corrugated cardboard and cardboard L- and C-shapes.

§ 2.4 The production of paper

Paper is a material of organic origin, the most popular raw materials from which paper is made are deciduous and coniferous trees. However, paper can also be made out of other plants, such as straw, hemp, cotton, bamboo, cane and other cellulose-containing materials. Moreover, using recycled paper as a source material is more and more popular.

Paper production is divided into two phases. First isthe preparation of paper pulp, second is processing the pulp in paper mills to form paper sheets (see Fig 2.18).

Pulp consists of small, elongated plant cells that form a compact tissue made of the 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.

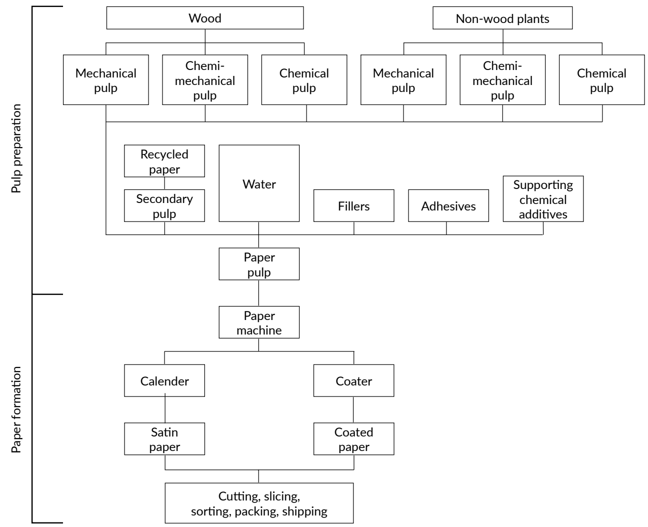

FIGURE 2.18 General scheme of paper production

Figure 2.18 presents the paper production process, including the preparation of the pulp with additives and fillers, and the formation of paper in the paper machine. Calendering is a process during which paper is run through rollers. It derives its smoothness and glossy properties from the application of pressure and heat. Coating is a process that can be applied in the paper machine or elsewhere. Special coatings which are applied to the outer layer of the paper may, for instance, create barrier properties for special paper such as the impregnated or paraffined cardboard used in the building industry.

§ 2.4.1 Raw material for paper production

The main raw materials used for paper production are coniferous wood (spruce, pine, fir, larch, western hemlock and Douglas fir) and deciduous wood (birch, poplar, aspen, beech, alder, acacia, oak, hornbeam and eucalyptus). [14] Recycled paper products, too, are becoming increasingly popular as a source of pulp. In 2014, the recycling rate reached 71% in CEPI countries (Austria, Belgium, Czech Republic, Finland, France, Germany, Hungary, Italy, the Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, the United Kingdom). The recycling rate is the percentage of paper that is used for recycling, compared to production of paper and board. [19] Cellulose fibres can be also obtained from fast-growing trees such as poplar, from straw or from plants with a fibrous structure, such as reed and hemp.

§ 2.4.2 Wood structure

Paper is produced out of cells that form xylem tissue (wood), a part of a tree situated between the pith and the bark. Pith functions as a physiological part of the tree, it stores and transports nutrients through the tree. Xylem arises from vascular cambium.

Bark, being the external protective layer for the tree system, consists of outer bark (which is comprised of dead rhytidome tissue), which serves as a protector from mechanical impacts, pathogens and the atmosphere, and inner bark (which is comprised of living phloem tissue), whose role is to conduct sap or nutrients (see Fig.2.19). Bark is not a desirable ingredient of paper, as it only features about 14-45% cellulose, 15-40% lignin and a high percentage of contaminants, which decrease the quality of paper. [4]

A thin layer of creative cells lies between the bark and xylem tissue. This is vascular cambium, which is responsible for the growth of the tree. Xylem tissue consists of two things: sapwood (which is situated on the outer side of the trunk and transmits saps such as water and soil nutrients up to the leaves) and heartwood (which is situated on the inside of the trunk and gives the tree enough strength to support its crown and keep the tree in place in strong winds).

Wood rays extend vertically through the tree, perpendicular to the growth rings. Wood rays store and move food laterally from the phloem to the living cells of the cambium and sapwood.

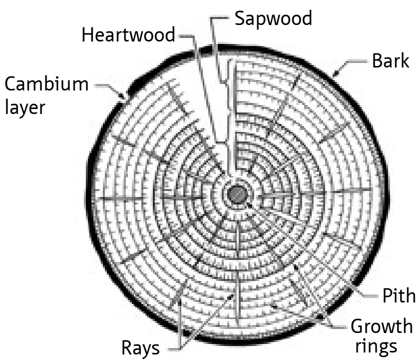

FIGURE 2.19 Transverse section of trunk

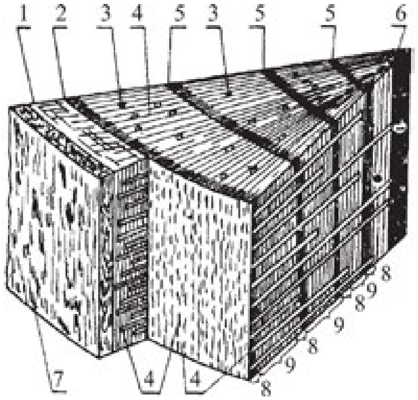

FIGURE 2.20 Diagram of the 4-year-old pine trunk: 1 - phloem, 2 - cambium, 3 - resin canals, 4 - rays, 5 - growth ring, 6 - pith, 7 - bark, 8 - latewood, 9 - earlywood

Wood consists of many cells which are different in size and shapes, depending on their function:

- Tracheids – these occur only in softwood, of which they are a dominant element (over 90%). Tracheids are elongated and slender cells serving as a conductive and mechanical support.
- Libriform fibres – a basic component of hardwood that serves as a reinforcing tissue. They have the shape of long, pointed cells.
- Vessel elements – these occur only in hardwood as a conductive feature; their cells are varied and specific to different species of trees.
- Parenchyma cells – these occur in both hardwood and softwood; they are part of the tissue, forming medullary rays and resin-lining channels. Parenchyma cells are an undesirable component of pulp.

Tracheids and vessels are called tracheary elements.

Both coniferous and deciduous trees are used for paper production. However, their structures differ, which greatly affects the properties of the resulting paper.

Conifers, also known as softwoods, have a simpler anatomy, which consists of 90-95% longitudinal fibre tracheid, 5-10 % ray cells and 0.5-1.0% resin cells.

Hardwoods have more complex structures. The cellular composition of hardwood is 36-70% libriform fibres, 20-55% vessel elements, 6-20 % ray cells and about 2% parenchyma cells. [4]

§ 2.4.3 Wood fibre structure

Wood fibres are elongated wood cells that provide mechanical strength and water transport through openings called pits (see Fig. 2.22). The fibres have hollow centres (lumens) and are heterogeneous in nature.

The most distinctive elements that constitute the xylem cells are the long tracheary elements that transport water. Two types of tracheary elements can be distinguished: tracheids (in softwood) and vessels (in hardwood) (see Fig. 2.21).

In softwood tracheid cells constitute 90-95% of the wood. In hardwood vessels and libriform fibres constitute approximately 65-70% of the volume of the xylem.

FIGURE 2.21 Hierarchical structure from the tree to the cellulose molecule

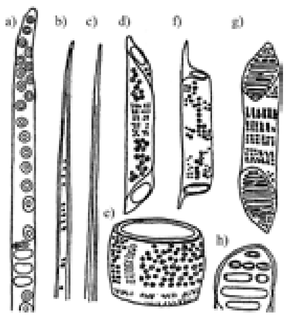

FIGURE 2.22 soft and hardwood cells: **a)** pine vessel, **b)** libriform fibers of apple-tree, **c)** libriform fibers of oak **d), e)** vessel element of oak, **f)** vessel element of apple-tree, **g)** vessel element of alder, **h)** front wall of vessel

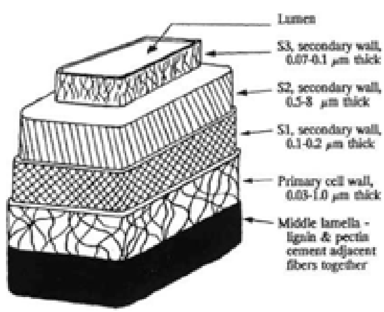

FIGURE 2.23 A mature softwood fiber

The quality of paper depends on the length and slenderness of the fibres used, as well as their resilience. The longer, slimmer and more flexible the fibres, the stronger the paper made out of them. In order to describe the slenderness of fibres, a ratio of length to width is used. The stiffness of the fibres is described by a stiffness index, which is the ratio of twice the thickness of the cell wall to the diameter of the lumen cells.

THE TYPE AND SPECIES OF TREE	DIMENSION OF THE CELLS			SLENDERNESS RATIO	STIFFNESS INDEX
	length (mm)	Width (μm)	Thickness of the wall (μm)		
Softwood (coniferous)					
pine	3,3	37	4,5	90	0,3
spruce	3,2	32	4	100	0,3
fir	3,1	36	4	90	0,3
Hardwood (deciduous)					
birch-tree	1,1	22	4,5	50	0,7
poplar	1,2	24	4	50	0,5
beech	1,0	20	5,5	50	1,2
oak	0,8	18	6	45	2,0

TABLE 2.1 Dimensions of wood fibers

As Table 2.1 shows, the cells of coniferous trees are longer, more slender and more flexible (less stiff) than the cells of deciduous trees. Therefore, they are more likely to create a strong bond during the paper-making process, which makes them more suited to the production of strong paper for packaging purposes, while the cells of deciduous trees are more suited to the creation of printing paper.

The shape of a single wood fibre causes anisotropy (see Fig. 2.22). Each cell is much stronger in its longitudinal direction than in its transverse one. Additionally, the composition of cells built out of smaller fibrils makes them much stiffer in their longitudinal direction.

Wood fibre walls have a layered structure. Each of these layers is characterised by a specific arrangement of fibrils. [24] There is a clear distinction between the primary and secondary walls (see Figs. 2.23 – 2.25). The secondary wall is divided into three different layers: the outer secondary layer (S1), the middle secondary layer (S2) and the inner secondary layer (S3).

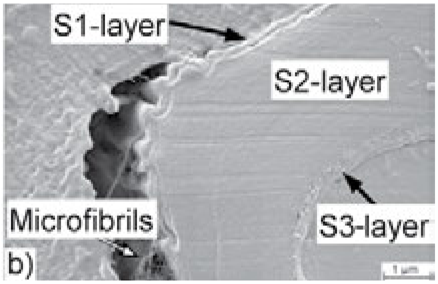

FIGURE 2.24 Transverse section through the cell walls of wood fiber

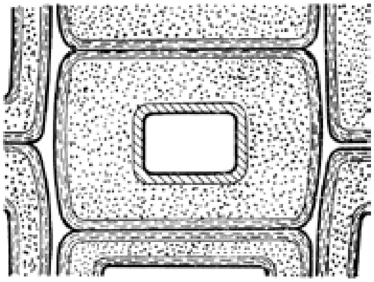

FIGURE 2.25 Structure of wood pulp fiber – microtomed cross section

The S2 layer of the secondary wall of the wood fibre is the thickest layer and dominates the overall properties of the fibre. The S2 layer has a chiral or helical structure made of micro-fibrils. The cellulose micro-fibrils are oriented at 10-30 degrees from the main longitudinal axis of the fibre. As a result, the fibre has great tensile strength in this direction. [2]

The elastic modulus is controlled by the amount of cellulose in the fibres as well as the micro-fibril angle. The higher the amount of cellulose and the lower the MFA (micro-fibril angle), the higher the elastic modulus.

The walls of plant fibres are composed of cellulose, hemi-cellulose, lignin, extractives (pectin) and minerals. The layers are complex biocomposites made of cellulose fibril aggregates embedded in a matrix of hemi-cellulose and lignin. The composition of the walls of fibres can vary depending on the species and type of wood – i.e., whether it is softwood or hardwood (see Table 2.2).

TYPE OF WOOD	CELLULOSE	HEMICELLULOSE	LIGNIN	EXTRACTIVES	MINERALS
	%				
Softwood	42	27	28	1 – 5	0,5 – 1
Hardwood	44	33	20 – 22	2 – 4	0,5 – 1

TABLE 2.2 Chemical composition of hard- and softwood

§ 2.4.4 Physical properties of wood

The most important physical properties of wood as a source material for paper production are density (the ratio of weight to volume) and moisture (the percentage of water in tested material). The moisture content of wood processed in paper mills is about 30%. [23] Another important characteristic property of wood is its absorbability, which is its susceptibility to absorption of aqueous solutions.

Hardwood is denser than softwood, and thus provides more pulp from the same volume of raw material. Hardwood also has higher absorbability, which positively affects the pulp-producing process.

§ 2.4.5 Chemical composition of wood

Wood is composed mainly of organic substances. The most important substances for the paper industry are cellulose, hemicellulose and lignin. Cellulose is the most valuable component of the wood used in paper manufacturing. Together with hemi-cellulose it forms the backbone of the cell membranes of wood. Depending on what pulping process is used, different amounts of hemi-cellulose and lignins may be present between the cellulose micro-fibrils.

An important difference between the structure of hardwood and the structure of softwood is its chemical composition. Softwood has a higher lignin content than hardwood. Cellulose content in both conifers and deciduous trees is approximately 40 percent.

§ 2.4.6 Cellulose

Cellulose is the main structural fibre of the plant kingdom. In the words of Klemm et al. (2005), *cellulose is the most common organic polymer and is considered as an almost inexhaustible source of raw material for the increasing demand for environmentally friendly and biocompatible products*. [25] The global production and decomposition of cellulose is ~1.5 x 10^{12} tonnes per year, which is comparable to the planetary reserves of the main fossil and mineral sources. [26]

Cellulose is the most valuable material and main component of the plants used for paper production. The extraction of cellulose in its fibrous character is the basic process of pulp production.

Cellulose is a natural multi-molecular compound, belonging to the polysaccharide group. The macromolecule has a chain structure in which the so-called glucose residues are linked by β-glycosides bonds. Together with hemi-cellulose it builds the skeleton of the cells. Cellulose is a colourless, insoluble fibrous substance with a density of 1.58 g/cm^3. [14] A single cellulose fibre has an elastic modulus of about 130 GP, and its tensile strength is close to 1 GPa. [10]

The subsequent (from smallest to biggest) cellulosic components of cellulose are:

- the cellulose molecule with the dimensions of 0.853 nm width, 0.395 nm thick, 2µ length (see Fig. 2.26),
- the elementary fibril,
- the microfibril (see Fig. 2.27),
- the macrofibril and the cellulose fibers (see Fig.2.28).

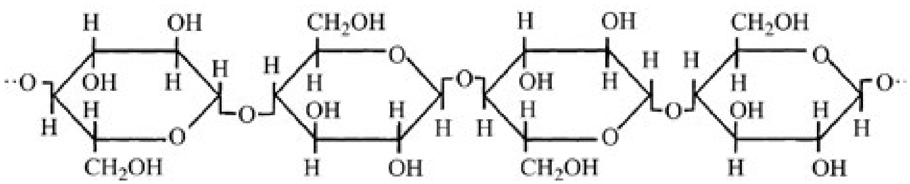

FIGURE 2.26 Cellulose molecule

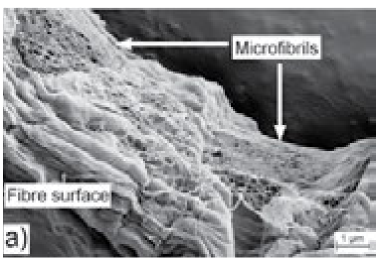

FIGURE 2.27 Cellulose fiber and microfibrils

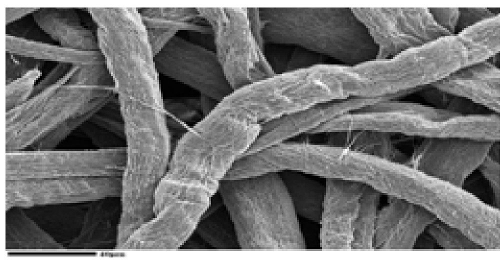

FIGURE 2.28 Cellulose fiber

The elementary fibrils are universal structural units of natural cellulose, as the same biological structure was encountered in cotton, ramie, jute and wood fibres. The bundling of elementary fibrils into micro-fibrils is caused by purely physically conditioned coalescence as a mechanism of reducing the free energy of the surface. [24] Aggregations of 200- 400 micro-fibrils create macro-fibrils.

Cellulose is produced when D-glucose polycondensates. The by-product this reaction is water. The synthetisation of the multi-molecular compound is called polymerisation and the product is a multi-particulate compound polycondensation homopolymer: polysaccharide.

Cellulose is a long linear homopolymer composed of 3,000-14,000 β-D glucopyranose ($C_6H_{12}O_6 - H_2O$) units linked by (1→4) glycosidic bonds. [10, 14]

The number of glucopyranose units describes the length of the cellulose chain. This is called the *degree of polymerisation* (DP).

The DP for cellulose molecule in wood is approximately 3,000-6,000. There are crystalline areas in cellulose molecules, which cause the cellulose to be insoluble in water.

The polymerisation structure of cellulose can be changed by chemical agents (hydrolysis, oxidation), physical conditions (temperature, light, mechanical grinding) and biochemical factors (enzymes produced by fungi and bacteria). During the pulping, the DP number of cellulose fibres decreases to 700-3,000.

Bonds are easily formed between the macromolecules of cellulose hydrogen. Such bonds bind together macromolecules, which results in the formation of filamentous fibrils. Intertwined fibrils build a skeleton of cells. Hydrogen bonds are also formed between the cellulose fibres. This phenomenon is crucial in the process of paper-making. Due to the organised structure of cellulose chains and the type of bonds between fibrils, cellulose is resistant to many chemical agents, but at the same time it is sensitive to hydrolytic degradation (decomposition under the influence of water) in an acidic medium.

§ 2.4.7 Hemicellulose

Hemi-cellulose is a polymer of different types of saccharides, not just of glucose residues, like cellulose. Its degree of polymerisation (DP) is much lower (less than 300), which results in weaker and degradable bonds. In the process of creating pulp, most of hemi-cellulose is degraded, while the remaining molecules have a positive impact on the process of creating paper. They are the natural glue that facilitates the bonding of fibres. Hemi-cellulose has a much lower elastic modulus than cellulose. As a result, the elastic modulus of paper pulp fibre can be lower than the elastic modulus of cellulose. [2]

§ 2.4.8 Lignin

Lignin is a natural organic multi-particulate compound with the spatial structure of polymer. Lignin can be found both between wood cells and within cell walls. It possesses mechanical properties that make the cell rigid and provide it with a stable structure. Lignin is an undesirable ingredient in the process of paper-making. Its presence causes hardening and the deterioration of the mechanical properties of paper. Lignin is removed in the pulping process.

§ 2.4.9 Other components of wood

Extractives (resin, waxes, fats, essential oils, dyes, etc.) account for 5% of wood by weight. These substances may affect the properties of wood pulp. They affect resistance to micro-organisms, but they have a corrosive effect on the production apparatus. Minerals are present in minimal quantities.

§ 2.5 Paper-production process

Paper production consists of several stages. Raw material in the form of wood is first prepared to be cut into smaller pieces and decorticated. Then wood chips are sent to a digester, where they are defibrated. The next stage is to screen for and reject particles bigger than desirable. This process is followed by pulp washing, bleaching and refining. Finally the pulp is transported to the paper machine, which produces paper in the form of a sheet. The final product can be refined by superficial additives in order to ensure that it maintains its desired properties, such as water resistance, incombustibility, etc. The steps making up the process are described below in order to provide a better understanding of the process of paper-making (see Fig. 2.29).

1 Preparing the wood – sawmill
  - a Slasher deck
  - b Barker

2 Storage – wood in the form of logs or chips is stored in warehouses or outdoors, in the open air. This can result in the decay of the wood due to atmospheric conditions, fungi, bacteria and insects. Coniferous wood is more resistant to decay than deciduous wood.

3 Chipping in the wood-chipper. The next step in the preparation of pulp is chipping. Wood logs are cut into small chips about 10-30mm long, 10-20mm wide and 2-8mm thick. The chipped wood is then treated with pulping chemicals. Chips that are oversized are removed and sent to the chipper again. Chips are assessed for their size. For the Kraft cooking process, chip thickness is of primary concern.

4 Digester – this is a pressure vessel in which wooden chips are cooked in order to soften and pulp them. Chemical, mechanical and chemi-mechanical pulping processes are carried out in the digester.

5 Pulp screening – this is the process in which pulp is separated from knots, dirt and other debris. Rejected particles are removed by screens and are sent to the digester again or removed.

6 Pulp washing – this is a process in which pulp is washed in water to remove chemicals and lignin. Certain chemicals, like black water, are recovered, filtrated and used again in the pulping process.

7 Pulp bleaching – bleaching involves treating wood pulp with chemical agents in order to brighten it. Pulp is chemically bleached by lignin removal. The removal of lignin

results in better inter-fibre bonding, but at the same time, the strong chemicals used for bleaching can weaken cellulose fibres by decreasing the length of their molecules. Mechanical pulp can also be bleached, by chemically altering the lignin molecules that absorb light. [4] Lignin removal is accompanied by a significant loss of pulp yields and also has a negative effect on the strength of the individual fibres. However, the strength of inter-fibre bonding increases after bleaching.

8 Pulp refining – this is a mechanical treatment given to pulp fibres in order to bring out their optimal properties. Refining increases the strength of inter-fibre bonds by increasing the fibre surface area. It also improves the formation of sheets on paper machines. The refining process increases the flexibility of the fibres and results in the creation of denser paper. Pulp refining involves fibre brushing (roughening the surface of the fibres in order to improve inter-fibre bonds), fibre cutting, water drainage, fibrillation (mechanical dishevelling of the fibres, e.g. by breaking the primary fibre walls). The Hollander Beater mentioned earlier is also a pulp-refining machine.

9 Paper machine – this is a device for continuously forming, dewatering, pressing and drying a web of paper fibres. Previously prepared stock consists of chemical, chemi-mechanical, mechanical or recycled pulp and a mixture of all these things is sent to the paper machine. The quality of the paper is determined by the quality of the prepared pulp. The pulp is pumped into the headbox of the paper machine and is mixed with water and some other chemical additives. Such an aqueous slurry consists of 99% liquids and 1% fibres when producing printing paper, and of 99.7% liquids and 0.3% fibres when producing strong packaging paper. The greater the percentage of liquids in the slurry, the better and more equal the spread of the fibres, and thus the mechanical properties of the end product. Next the slurry is spread from the headbox through the slice on the wire. This process, which is called the forming, is the most important part of paper-making, and at the same time the most difficult one. The formation process takes place in a former on the flat wire, also known as a Fourdrinier (with a maximum speed of 800m/min), cylindrical sieve (with a maximum speed of 400 m/min) or twin wire machine. The cylindrical sieve, although it is slower, is suitable for the production of multi-layered cardboard, decorative paper, banknotes, securities and other long-fibre papers. [14] After the forming, the paper web is drained, pressed and dried.

10 Paper conversion – the last process in a paper-making machine, in which paper is coated, calendared or treated with additives designed to give it certain special features. The process of paper-coating can be compared to the plastering of a wall before painting. The holes in the wall (porous in the cellulose fibre network) are filled with a paste that is sheared onto the surface of the paper. [2]

11 Rolls or sheets of paper are now shipped to the customer.

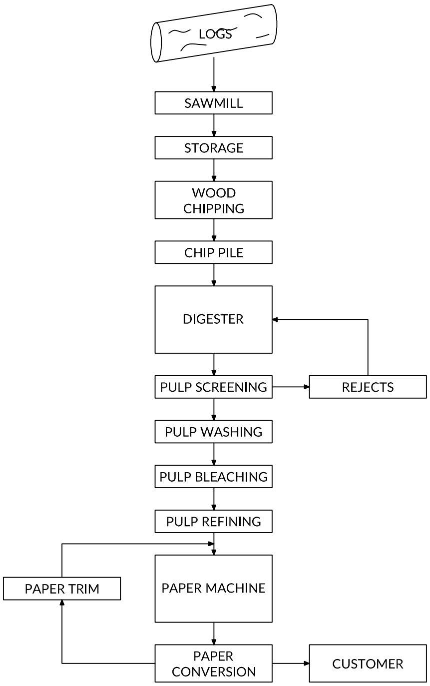

FIGURE 2.29 Paper production scheme

§ 2.5.1 Pulp production methods

Pulp is obtained by means of mechanical, chemi-mechanical, semi-chemical and chemical processes. Pulp consists of cellulose fibres, hemi-cellulose fibres and lignin, derived from vegetable materials (wood, stalks, straw, hemp) or from recycled paper products. During the pulping process the outermost layers of the wood fibres, which hold together the wood, are partly or completely removed. As a result, the fibres disintegrate in the pulping process. [2]

Pulp is also the source material for products other than paper, such as fibreboard and MDF (medium-density fibreboard), as well as a component of certain plastics and composites. The raw materials that are suitable for paper production are cellulose and hemi-cellulose. Lignin, on the other hand, is an undesirable part of the pulp, since it makes paper stiff and brittle. The following methods can be used to remove lignin from the pulp or reduce its impact on the properties of paper:

- **The mechanical method** involves refining, crushing and separating the wood fibres in order to obtain wood pulp. Thermal treatments are also provided during the refining process to soften the lignin. The pulp thus obtained is called thermo-mechanical pulp (TMP). The product resulting from the mechanical treatment of groundwood is used in the manufacture of paper and fibreboard. The mechanical method is the most efficient way to produce pulp (95-97% yield). Pulp resulting from a mechanical process contains lignin. In order to get rid of this lignin, a chemical process of discolouring lignin polymers is used (so-called whitening). This process is reversible over time, which results in the yellowing of printed matters produced from mechanical pulp. Due to its lignin content, pulp produced by the mechanical method is only suitable for newsprint (non-archival paper); it is not appropriate for the manufacture of durable packaging paper, so it is not suitable for use as an architectural material, either. Currently mechanical pulp accounts for 20 percent of all virgin fibre material. [11, 28]

- **The chemo-mechanical method** or chemo-thermo-mechanical pulp (TCMP) consists of two stages. First a chemical solution is added to wood chips or logs in order to soften the wood. Then the logs are pulped by means of a stone. The original lignin structure and content are preserved, but the extractives and some small amount of hemi-cellulose are lost. The pre-treatments used in the chemo-mechanical method are hot sulphite or cold soda. This method can be applied to hardwood to ensure high-quality pulp. The yield of the chemo-mechanical method is 85-95 percent. This pulp has properties that make it well suited to the manufacture of tissue paper.

- **The semi-chemical process** is a high-yield chemical process with yields of 60-80 percent. It involves two steps. The first step is to add a chemical treatment to the wood, followed by mechanical refining. In this method both lignin and hemi-cellulose are partly removed. The first step of the semi-chemical method is similar to other chemical methods, although it involves lower temperatures, shorter cooking time and less chemicals. The semi-chemical method is used to create corrugated cardboard with flutings.

- **The chemical method** (which involves sulphate, sulphite and soda) consists in dissolving and removing most of the lignin from the fibrous mass structure. This process results in a cellulosic pulp. Using sulphite results in a medium-strength pulp with soft, flexible fibres, and in yields between 40-52 percent with minimal lignin content in the pulp.

- **The sulphate method** is called **Kraft**, a name derived from the German word Kraft, which means 'strength' or 'power'. This method yields the strongest paper with the smallest amount of lignin, about 3-5 percent. [4] For this reason, the sulphate method is the most appropriate for strong packaging paper which can be applied in architecture.

§ 2.5.2 Kraft pulping method

Kraft pulping is a fully chemical method that involves sodium hydroxide (NaOH) and sodium sulphide (Na_2S). Wood chips are cooked in a digester at a temperature of 160-180 °C and a pressure of about 800 kPa for half an hour to three hours. During the cooking process, lignin is softened and the cellulose fibres are dissolved. Kraft pulp has a low lignin content, approximately 15% hemi-cellulose and 85% cellulose. [10]

All kinds of wood can be pulped with the Kraft method, and the presence of bark does not constitute a problem. The Kraft method has an efficient energy and chemical recovery cycle. The downsides of the Kraft method are the relatively low yield and the very smelly emissions caused by the sulphate used during the pulping process.

The yield of the Kraft method depends on whether the end product is white (bleached) or brown paper. For brown paper the yield is about 65-70%, and 43-45% after the bleaching. [4] Kraft is the most expensive method, but also produces the strongest end product.

Currently, the most popular method for producing paper pulp is the sulphate (Kraft) method. Approximately 80% of global pulp production involves the use of the sulphate method. The remaining 20% is produced by means of the mechanical and semi-chemical methods. [14] This is due to the strength properties of the mass obtained by these methods (compared to the sulphate method), the fact that any type of wood can be used, and the development of production systems that minimise the discharge into the drain.

Before being formed into paper, pulp may be subjected to chemical processes and whitening treatments, and it is the additives that cause the release of the cellulose.

The Kraft pulping method is the preferred method to produce strong paper that may be used as an element of architectural structures. Due to the single-fibre properties, the best paper for architectural use is softwood Kraft paper.

§ 2.5.3 The properties of pulp

The properties of pulp are described in the following terms:

- The degree of digestion, which is the process of delignification defining lignin content by weight after the chemical digestion process. The lower the lignin content, the more flexible and durable the end product. The pulp's degree of digestion is determined by its kappa number, which is determined by performing an analysis of the ratio of delignification agent (e.g. potassium permanganate) to the amount of pulp. There are three types of pulp: hard with a high lignin content, normal and soft with a low or non-existent lignin content, and bleached pulp, which is completely free of lignin.
- Pulp viscosity, which is an average cellulose chain length described by number of polymerisation DP. Higher viscosity indicates stronger pulp and paper.
- Grindability, characterised by the pulp's susceptibility to mechanical grinding.
- Moisture content, which is determined by drying some pulp in an oven and compering its weight to that of undried specimen.
- Strength properties, which are the most important properties from an architectural point of view. The strength properties of tested specimens are divided into tensile strength (indices: self-tearing and extensibility), puncturing (burst ratio), tear (tearing resistance index), bending (index number of double bends) and hardness, rigidity, torsional rigidity and resistance to breaking.
- Fibre length – the standard fibre length measured in the pulp
- Colour of the pulp – whiteness indicator
- Pulp purity – the basis for the categorisation of pulp, used to determine the extent to which the pulp is polluted by other molecules, e.g. bark, coal, carbon, etc.
- Special features of the pulp required for the production of paper for special uses, e.g. blotting paper (absorption), electric paper, writing paper (high opacity), etc.

§ 2.5.4 Paper making process

The paper-making process consists of four stages, which in general can be described as:

1. Forming and draining
2. Pressing
3. Drying
4. Callendaring

A slurry consisting of 99%-99.7% water and chemical additives and 0.3-1% pulp fibre is poured onto a travelling mesh or rotating cylinder which is used for heavyweight boards. [4, 28] The greater the amount poured onto the machine, the thicker the paper. The fibres are aligned mostly in the direction of travel and interlace in order to improve the formation of the sheets of paper. During this process, cellulose fibres create hydrogen bonds between each other. The same principle is used for both machine- and hand-made paper.

The next step is removing the remaining water from the fibre web formed in the previous step. This is done by means of vacuum boxes and pressing sections (after which the paper will have a 65% moisture content) and later by drying parts of the paper machine by means of steam. At the end of this process, the moisture content of the paper is equal to 3-6% (see Fig. 3.30).

Paper products can also be converted into special types of paper, or alternatively, their properties, such as smoothness and gloss, can be improved by coating, calendering, etc. This is done when the paper has a moisture content of 3-6%. If a special type of paper is to be manufactured, the next step of the finishing or conversion process starts here. However, for regular paper this is the final step, and so the paper is wound on a roll in the desired dimensions, sorted or packed and shipped to customers.

During the paper-making process, after draining the pulp, the planar fibre network is held together by surface tension forces, which gives paper its viscoelastic character. Afterwards, the paper web is pressed by rollers and heated by hot cylinders to remove the remaining water. In this process the water menisci between the fibres shrink and pull the fibres against one another so that hydrogen bonds are created at the molecular contact between the adjacent fibres. These bonds between the fibres are the factor determining all the mechanical properties of paper. In wet conditions the helix of the fibre wall is swollen, more in the transverse direction than in the axial direction. When paper is dried, the anisotropic shrinkage leads to internal stresses in the fibre network. This is caused by the axial stiffness of the fibres, which resist transverse shrinkage. Paper that dries under tension has a larger elastic modulus than paper that was free while drying. The tension maintained in the paper machine in the machine direction (MD) prevents shrinkage during drying. Like the orientation of the fibres, this causes paper to have better mechanical properties in machine direction (MD) than in cross-machine direction (CD). [2]

Chemical and energy recovery make up an essential part of paper process. Half of the raw material provided by the wood is utilised as chemical pulp fibre, while the other half is utilised as fuel for electricity and heat generation. The chemical pulping process generates more energy than it uses. Extra energy produced by paper mills can be sold and transmited to the electricity grid. [28]

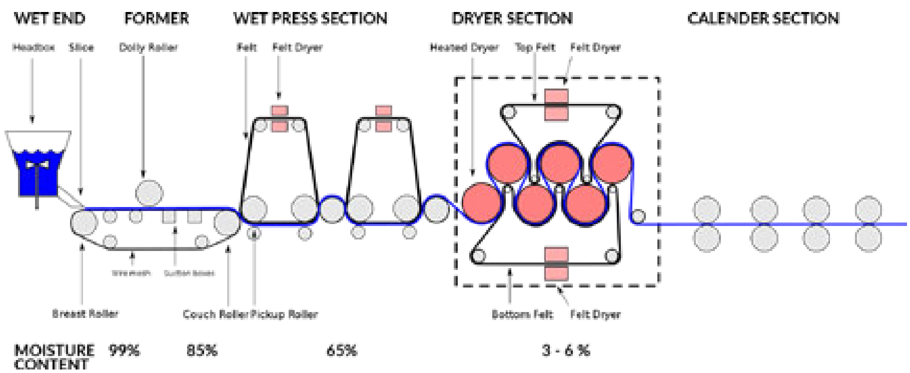

FIGURE 2.30 Diagram of Fourdrinier (flat sieve) paper machine

§ 2.6 The properties of paper

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

This section will discuss those properties of paper that have a significant impact on the extent to which paper can be used as an architectural and structural material. This means that optical properties, such as brightness, transparency, colour, smoothness, glossy finish, etc. will not be discussed here, as they are irrelevant to architects.

§ 2.6.1 The chemical and physical structure of paper

As paper is made out of cellulose fibres, it is possible to distinguish its properties on a micro- and macro-structure level.

The micro-structure of paper is based on fibrils. Fibrils are the smallest parts forming paper. Fibrils are composed of cellulose chains with a maximum length of 5μm. [22] Bundles of extended-chain molecules are arranged into monodisperse fibrils which form fibril aggregates. Bigger fibril aggregates form lamellae or cell walls. Thanks to their highly crystalline fibrous structure and strong network of hydrogen bonds, cellulose fibrils are insoluble in water and have great mechanical strength.

The mechanical properties of paper can vary, even between sheets of paper made out of the same pulp. The mechanical properties of fibres and bonds are influenced by the paper-making process. Fibres in sheets of paper are oriented randomly, so each production series may differ. The more bonds are created between cellulose fibres, the stronger the paper. The points at which the fibres overlap create bonds between fibres. The mechanical properties of paper are governed by fibres and the bonds between them.

§ 2.6.2 The structural characteristics of paper

Paper's web-like structure, consisting of wooden fibres, can be visualised by comparing it to cooked spaghetti that is served on a plate (see Fig.2.31). This plate of spaghetti resembles paper after it has been drained and allowed to dry. However, the significant difference between the simplified example of spaghetti and paper lies in the helical internal structure of wood fibres. [2] During the paper-making process, after draining the pulp, the planar fibre network is held together by surface tension forces, which give paper its viscoelastic character. The length of a single fibre ranges from 1 to 3mm (which is approximately ten times more than the thickness of a typical sheet of paper), and the width and thickness of a single fibre range from 10 to 50 μm. [10] There are ten to forty inter-fibre bonds per fibre in a sheet of paper. The structure of paper is very close to a fully random, uncorrelated planar fibre network. [2] The number of fibres per unit area is described in terms of basis weight or grammage [g/m^2].

The thickness of paper is always specified by the grade of the paper. The thickness of paper can vary depending on the moisture content of the material. Common printing and writing paper is about 0.1mm thick. Cardboard can be 0.3 up to 4mm thick.

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.

The porosity of paper (whose level is determined by its density) has a significant impact on the other properties of paper. Porosity is the ratio of pore volume to the total volume of a sheet of paper. It is akin to air permeability, which is the property of paper that allows air to flow through a sheet of paper under changing pressure conditions. Air permeability is a structure-related property of paper and is inversely related to its strength properties. It also affects paper's resistance to water and other liquid reagents. [18]

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) (see Fig.2.32). [30]

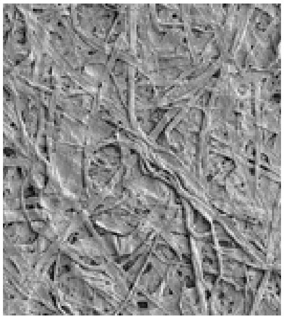

FIGURE 2.31 Magnified wood pulp paper

FIGURE 2.32 Magnified edge of a paper

§ 2.6.3 The mechanical properties of paper

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 smallest particle of paper, which is the wood cellulose fibre, has an elastic modulus of around E = 35 GPa, and its ultimate strength is σ = 120 MPa. It is much smaller than pure cellulose molecule fibres, due to the cellulose micro-fibril angle (MFA), which varies by 10-30° from the main longitudinal axis of the fibre. These values are not equal to the values of paper as other factors influence the final mechanical properties of paper. [10] 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.). As stated before, 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.). [31] In other words, the properties of paper depend on different factors affecting the material at both the fibre level and the network level.

What 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 and in the same paper machine.

In general, paper and cardboard are inhomogeneous, anisotropic, non-linear, visco-elastic-plastic and hygroscopic materials. [31]

During the production processes in the paper machine, about 70-80% of the fibres are oriented in the direction of the machine ('machine direction' or 'MD'), while 20% are oriented perpendicularly ('cross direction' or 'CD'), and 10% are oriented in the direction of the thickness of paper. [32] It is this configuration of the fibres that gives paper its anisotropic characteristics, because MD fibres are stronger than CD fibres. The MC/CD ratio depends on the nature of the fibres and the production process, so it is not possible to set this value as a constant.

Paper is stronger in tension than in compression, as can be seen from the graph presented by Schonwalder. [31] The graph also shows that the tested specimens behaved differently in MD and CD (see Fig. 2.31). Paperboard tested in CD was less stiff, weaker and quicker to deform. As Schonwalder noted, the tested specimen showed a relatively brittle failure, which means that there was no significant plastic deformation before breaking. The very ends of the compression curves show post-peak behaviour, which means that paper loaded with maximum force can still carry some forces, which is important information from a structural safety point of view.

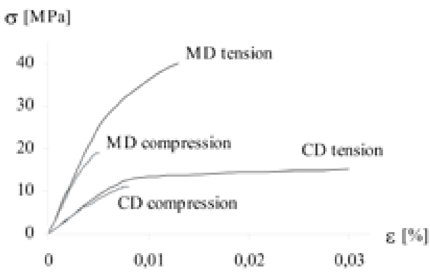

FIGURE 2.33 Typical stress-strain curves of solid board for tension and compression in MD and CD

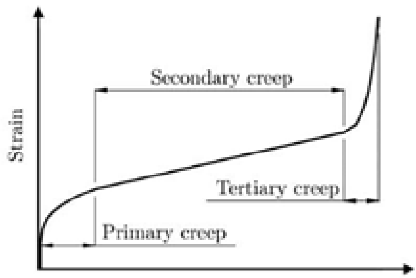

FIGURE 2.34 General shape of the creep curve of paper

The elastic modulus of paper and board ranges between 2 and 20 GPa, and typical value is 5 GPa. The differences in the elastic modulus can be seen in MD, which is 1.5 to 4 times higher than the elastic modulus in CD. The modulus is the same for compression and tension in the respective fibre directions.

The tensile strength is 15-45 MPa, but there are types of paper with a tensile strength of up to 80 MPa. Tensile strength in CD is 0.3-0.5 of the tensile strength in MD.

The compression strength of paper is smaller than its tensile strength. Its compression strength is 0.3 to 0.5 of its tensile strength. Its compression strength in CD is approximately half of its compression strength in MD.

The breaking strain under tension is 1.5-2.5% in MD and 3-4% in CD. The breaking strain under compression is 0.25 of the tensile breaking strength in MD and 0.2 in CD. [31]

The stiffness of paper is two to four times greater in MD than in CD. The bending stiffness depends on the thickness of the paper and its elastic modulus. Failure in bending is caused by fibre buckling at the compression side of the paper sheet. [13]

According to Schonwalder, Poisson's ratio (ν), which describes the ratio of lateral strain to axially applied strain under a longitudinal load, is usually ν_{MD} = 0.4 and ν_{CD} = 0.1

for paper. However, Szewczyk states that Possion's ratio is one of the most difficult to determine for paper, and he assumes that it ranges from 0 to 1. [33]

The share modulus G was estimated by Schonwalder to be one-third of the geometric mean of Young's modulus in MD and CD, $G \approx 1/3(E_{MD}\, E_{CD})^{1/2}$.

In order to compare the mechanical properties of paper with traditional building material their properties are listed in Table 2.3. Steel, concrete and glass are strong and stiff materials, but on the other hand they are heavy. Paper has a weight density comparable to wood. Wood similarly to paper is anisotropic material. Wood is stronger in grain direction while paper in machine direction. The table shows that cardboard fits into the range of building materials however it has very low stiffness. The data presented in table were gathered by Julia Schonwalder. The table includes the outcomes of tests performed by Schonwalder on a solidboard with the grammage 1050m/m².

ISOTROPIC	Modulus of elasticy [GPa]		Ultimate stress compression [MPa]		Ultimate stress tension [MPa]		Weight density [kN/m³]	Em-bodied energy [MJ/kg]	Recycling
Concrete C20/25	29		20		2.2		24	1.9	downcycling
Steel Fe E235	210		360		360		78.5	25	recycling
Glass (EN 572-1) Float glass	70-75		700-900		30-90		24	13.7	recycling
Polyethylene	0.6-0.9		20-30		20-45		9.5	80.9	recycling
ANISOTROPIC	‖	⊦	‖	⊦	‖	⊦			
softwood	8.5-11	0.6-0.9	35-45	3-9	30-80	3-4	4.5-6	4.7	recycling
Paper	2-20	0.5-10	5-10	2-5	15-45	5-20	6-9	5-20	recycling
Solidboard	3.5	1.6	8.0	5.6	27.1	13.5	6.9	9.4	recycling

‖ *wood in grain direction, paper – machine direction*
⊦ *wood in perpendicular to grain direction, paper – cross-machine direction*

TABLE 2.3 Comparison of the properties of paper and traditional building materials

§ 2.6.4 Viscoelastic properties

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. Thee creep rate (φcr) varies, depending on the nature of the paper, forces, relative humidity and other factors. Three stages of creep can be observed in paper. First the strain in the material will increase rapidly. Then a linear increase in strain will become noticeable over time. Finally, a very rapid increase in strain and subsequent failure will occur (see Fig. 2.32). At a low level of stress the material may not enter the third stage of creep. [13] Fifty percent of the total strain is tertiary creep, which means that if material is kept at a lower stress level, it will never reach the stage of tertiary creep, and the creep strain will be significantly reduced. [10] If the stress level is never higher than 50% of the maximum load, paper will not experience tertiary creep. [34]

The creep rate of paper increases with increasing humidity. In paper that has fallen prey to creep, the cellulosic micro-fibrils slide past each other as rigid bodies. This sliding requires that all the bonds of such micro-fibrils break. This process is accelerated by moisture and variations in moisture levels. When paper ages, seasonal changes in humidity, changing temperatures and forces will cause a change in the mechanical properties from which the paper will recover slowly.

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.

§ 2.6.5 The influence of moisture on the properties of paper

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. If 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. [35] 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%. [36]

When the engineers of BuroHappold conducted their preparatory studies for the paper building to be erected at a primary school in Westborough, UK (see Section 4.3.8) , they found that the moisture threshold for the best mechanical properties of paper tubes is 7%. If this threshold is exceeded, the strength of the paper tubes decreases by 10% for every one-percent increase in moisture content. The sustainable moisture content of a tube is approximately 7-10% in a room with a humidity level of 30-70%, which is typical for UK interiors. [37]

According to research conducted at Lodz University of Technology's Institute of Papermaking and Polygraphy , paper has a moisture content of 6% when subjected to a relative humidity of approximately 50%. When subjected to a relative humidity of 90%, the moisture content of paper increases to 14%. [23]

Julia Schonwalder and Jan Rots of Delft University of Technology (TU Delft) report that paper has a moisture content of 5% at a temperature of 23°C and a relative humidity of 50%. If paper is subjected to a relative humidity of 90%, its moisture content rises to 14%, and at the same time its strength decreases by 50%. [38]

Tests on paper tubes used for Shigeru Ban's Paper Dome project, conducted by Prof. Minoru Tezuka at Chiba Polytechnic College's Department of Housing Environment in 1997, demonstrated that the strength of paper tubes decreases gradually up to a moisture content of 7%, then decreases radically with a moisture content between 7 and 13%, and shows a linear decrease when the moisture content exceeds 13%. At the same time, the paper's strength will decrease by almost 50% at 7% (approx. 110 kg/cm^2) and at 13% (less than 60 kg/cm^2). [39]

The aforementioned studies show that the optimum moisture content of paper is a moisture content of 7%. If the 7% threshold is exceeded, the strength of paper will significantly decline. In a relative humidity of 50%, the moisture content of paper that have not been impregnated is 5-6%. In a relative humidity of 90%, the moisture content of paper that have not been impregnated rises to 13-14%, and their strength is reduced by half.

As LC Bank and TD Gerhardt report, paper with a higher moisture content is likely to experience higher creep rates, but paper also exhibits accelerated creep when it is subjected to changes in the humidity level. [36] Changing humidity levels cause higher creep rates than even the highest (but constant) level of humidity.

The hydro-expansive strain or shrinkage is equal to zero when the moisture content is constant. After first two years the structures gain the moisture balance and there is no more shrinkage. Hydro-expansive strain is a linear and reversible function of moisture content (MC). Hydro-expansion is the hydro-expansive strain divided by the corresponding change of the moisture content. Hydro-expansion is typically three to five times larger in CD than in MD. [31]

The greatest risk for a structure made of paper is the moisture content of its material being affected by direct contact with water, e.g. rain or high humidity. Paper, being a fibrous material composed of cellulose fibres affected by water, undergoes hydrolysis when moist, which causes the fibres to dissolve in water. During the paper-making process, hydrogen bonds are formed between the fibres; these bonds are essential to the creation of paper. However, the bonding process can also be reversed under the influence of water and moisture. Thanks to the organisational structure of the fibres and the type of bonding between the cellulose fibrils, cellulose is resistant to many chemical agents, but it does have a sensitivity to hydrolytic degradation (decomposition under the influence of water) in an acidic medium. [23]

§ 2.6.6 The impact of fire on paper

A thin sheet of paper can burn easily. The ignition temperature of paper is 230°C. However, tests conducted on thicker cardboard show that the flammability of a paper tube is similar to the flammability of timber. The burning rate of paper depends on the density of the material. For dense cardboard it can be assumed that the burning rate is similar to that of wood (0.7 mm/min). [13]

Thicker paper is harder to ignite. A series of tests examining the flammability of the material was conducted on the occasion of the Local Zone project in the Millennium Dome in London. [10] By covering the tubes with the intumescent coating it was possible to obtain a class-0 flame spread over the surface (flammability) . The tests were carried out by Warrington Fire Laboratories, which awarded the appropriate certificate. The test results were sufficient to help the Local Zone project satisfy the applicable building codes Tests were carried out on uncoated and coated tubes. The edges of the tubes were subjected to fire at a temperature of 1,000°C, which resulted in a protective charred layer just like happens to wood. After being exposed to flames for sixty minutes, the 150mm tube was charred. The application of intumescent paint on the ends of the tube did not change the behaviour of the material.

§ 2.6.7 The impact of micro-organisms on paper

Like wood, paper can be destroyed by fungi and other micro-organisms. High humidity and high temperatures encourage bacterial growth. Impregnation or chemicals added to a paper structure can minimise the growth of micro-organisms and deter rodents. [13]

§ 2.6.8 Impregnation methods

A traditional method of impregnation involves the use of egg protein, but more tests need to be carried out on this solution.

Covering paper tubes with a layer of waterproof liner has been known to make tubes stronger and less prone to varying levels of strength in the external environment. Another option is to cover tubes with a layer of PVC, but this solution is not environmentally friendly.

Shigeru Ban in his patent documentation includes information on the possibilities of using paraffin to impregnate paper. However, in his projects he generally uses polyurethane liquid, in which the paper tubes are dipped. He also suggested using polyethylene to impregnate paper. [40]

Taco van Iersel of TU Delft's Faculty of Architecture proposed using PE foil to cover the paper components of buildings. [32]

Paper tubes can be impregnated during the production process. For example, the innermost and outermost layers of the tubes can be coated with polyethylene. Alternatively, the coated layer can be placed inside the paper tube, in such a way that the inner- and outermost layers will remain pure paper, but with a coated layer in between. This can improve the natural appearance of the tube, when used indoors, or allow contractors to put extra layers on the inner and outer surface, e.g. by dipping them in the repellent.

BuroHappold proposed covering paper tubes with polyethylene film, or alternatively, producing sandwich paper tubes in which the innermost and outermost layers are made of aluminium. [41]

BuroHappold also mentioned various types of paint and varnish. These are used in the production of paper canoes in the USA and Australia.

Bank and Gerhardt suggest the use of polyurethane-based or other impervious polymer coatings. [37]

In principle, there are two approaches to paper waterproofing. The first is the application of protective layers on the surface, and the second is internal impregnation of fibres.

§ 2.6.9 Paper grades

Paper products are classified as paper and paperboard. Paper products are distinguished according to the fibres used in their production, the production and pulping methods and the weight of the paper.

There are several grades of paper, whose categorisation depends on properties such as weight, usage, conversion, raw material or pulping method. Different countries use different weights to determine grades of paper.

The following weight-based grades of paper are recognised:

- **Tissue**: Low weight <40 g/m^2
- **Paper**: Medium weight 40 - 120 g/m^2
- **Paperboard**: Medium High weight, 120-200 g/m^2
- **Board**: High weight >200 g/m^2

According to the norm ISO 4046 1-5 of 1978, products with a weight lower than 225 g/m^2 are called paper, and products with a weight over 225 g/m^2 are recognised as cardboard. For multi-layered products the threshold is 160 g/m^2.

According to another categorisation, paper products under 150 g/m^2 are called paper, products between 150 and 500 g/m^2 are called paperboard, and products over 500 g/m^2 are called board. [10]

Almut Pohl (2009) recognises paper with a grammage between 80 and 300 g/m^2 as being appropriate for use of architecture. [13]

The following types of paper exist: [4]

- **Tissue** – lightweight paper of 15-60 g/m². Tissue paper is mostly made from chemically bleached softwood but also contains some hardwood pulp. It can also be produced from de-inked recycled fibres.
- **Groundwood paper**, which can be sub-divided into uncoated and coated groundwood paper. Groundwood paper is made of mechanical pulp to which some chemical pulp has been added for strength purposes. Uncoated groundwood paper is mainly used for newsprint and printing paper. Coated groundwood paper is used for magazines and offset printing.
- **Wood-free paper**, which, like the previous category, can be sub-divided into uncoated and coated paper. Uncoated wood-free paper is made of softwood subjected to Kraft or sulphite treatment, with the addition of some mechanical pulp and recycled fibres. This type of paper is used for envelopes, photocopy paper. Coated wood-free paper is used for the production of smooth and glossy printing paper for magazines, books, etc.
- **Kraft wrapping paper** or bags, made of bleached or unbleached softwood paper subjected to a Kraft treatment.
- **Cast-coated paper** – very glossy paper used for wrapping materials, carbon paper, wax-base paper and special types of paper.
- **Special paper** made for special purposes, which may include packaging, manufacturing or printing, or electrically conductive paper, cigarette paper or greaseproof paper.
- **Kraft paperboards** – paperboard is paper heavier than 134 g/m². Kraft paperboard comes in two varieties: unbleached and bleached. Unbleached paperboard is mainly used for packaging, i.e. for milk cartons, cups and plates. Unbleached paperboard is used to create linerboard and corrugating medium. The production of paperboard may well involve recycled fibres.
- **Chipboard and recycled paperboard**. Chipboard is a thick paper of low density. It is often used for low-strength fibre boxes. The source material is recycled newsprint or inexpensive pulp. It is used to produce gypsum linear, tubes and clay-coated folding boxboard.

Paper can be also graded according to its usage:

- **Newsprint paper** – characterised by a short lifespan, low costs and a high percentage of mechanical pulp. Newsprint paper tends to be between 40 and 64 g/m².
- **Bond paper** – used for high-quality printing or writing paper.
- **Fine paper** – high-quality and smooth paper used for both writing and printing.
- **Tissue** – soft and absorbent paper. Can be sub-divided into three categories: sanitary tissues, wrapping tissue and tracing tissue.
- **Glassine and greaseproof paper** made from refined chemical pulp, which results in very dense translucent paper.

- **Linerboard** – unbleached softwood paper subjected to the Kraft treatment. It is used for the outermost plates of corrugated board, which are combined with corrugating medium, with the machine direction perpendicular to the fluting in order to strengthen the corrugated board in both directions.
- **Corrugating medium** – made from unbleached semi-chemical pulp. Must have a high degree of stiffness and be crush-resistant.
- **Construction board** – a thick board used in the building industry, e.g. as an insulation board.
- **Moulded pulp products** such as egg cartons, flower pots, etc.

In a document dated December 2014 entitled 'Pulp and Paper Industry: Definitions and Concepts', CEPI (the Confederation of European Paper Industries) distinguished the following grades of paper: [11]

- **Graphic paper**
- **Packaging paper**
- **Sanitary paper**
- **Other types of paper and board**

§ 2.7 Paper products in architecture

Essentially, there are five products that 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-shape**s

§ 2.7.1 Paperboard

Paperboard is a generic term applied to certain types of paper characterised by relatively high rigidity. The first paperboard was produced in England in the early nineteenth century for packaging purposes. In the second half of the nineteenth century, folding boxes were invented, as were mechanical die cutting and creasing of blanks.

The following types of paperboard can be distinguished: carton board (board manufactured for the production of cartons with good folding and scoring properties), chipboard (board made of low-grade waste paper), solid board (board consisting of one or several layers of the same material) (see Fig. 2.35) or solid fibreboard (with a grammage exceeding 600g/m², which can be finished with a lining of Kraft paper or another strong type of paper). Paperboard has high density. The material can either have a homogeneous structure or it can be produced from several plies. Paperboard can be finished with a liner made of special paper, e.g. waterproof paper. The thickness of paperboard can range from 0.25mm to 4mm. Its grammage ranges from 224 g/m^2 to 1,650 g/m^2. Solid board is characterised by high strength and stiffness. [44] The structural behaviour of paperboard is affected by its number of layers, the direction of the fibres (MD or CD) and the type of adhesive used.

Tests conducted by Julia Schonwalder at TU Delft showed that, depending on the composition of the material and the type of adhesive used, paperboard has a tensile strength between 9.7 and 29.8 MPa in MD and between 5.9 and 15.5 MPa in CD. The bending stress ranged from 3.7 MPa for a 20-layered solid board beam laminated with polyvinyl acetate that was bent horizontally to 32.1 for an 8-layered solid board beam laminated with wood glue that was bent vertically (see Fig. 2.36). [45]

FIGURE 2.35 Paperboard

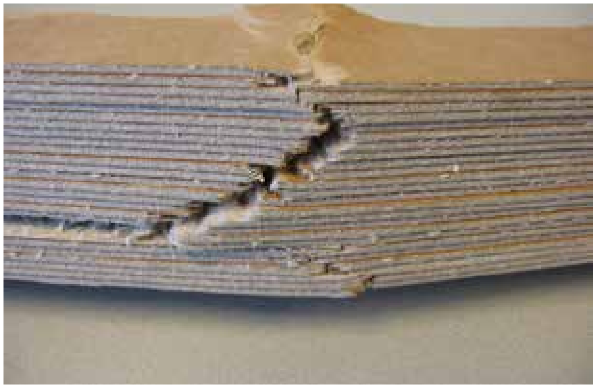

FIGURE 2.36 24 layer solidboard tested for bending

§ 2.7.2 Paper tubes

Paper tubes, also known as paper cores, are the most popular products of the paper industry used in architecture (see Fig. 2.37). This is because of the great popularity of Shigeru Ban's architectural projects. Tubes are mainly used by the paper industry and other industries for transportation and storage purposes. Paper towels, toilet paper, wrapping plastics, metal foil and many other products we come across in our daily lives are wound on small paper tubes, whose diameter ranges from 10 to 25mm, and the thickness of whose walls ranges from 0.5 to 1.5mm. Bigger tubes are used for rolls of printing paper, plastic film and textiles. The diameter of these tubes will be between 70 and 200mm, and their walls will be 10 to 25mm thick. [36] In the building industry, bigger paper tubes are used mainly as a disposable formwork for concrete columns. Such formwork tubes, also called Sonotubes as they were invented and patented by Sonoco Products Company in 1945, have diameters ranging from 50 to 1,600mm and may be up to 18m long. Another Sonoco products that can be used in architectural applications is a voided slab, in which paper tubes are placed horizontally before being cast in concrete.

There are two ways to produce paper tubes: parallel winding and spiral winding (see Fig. 2.38). Parallel winding consists in winding a sheet of paper with a fixed width around a core. Subsequent layers of paper are glued together. The length of the tube is determined by the width of the sheet of paper. Spiral winding consists in winding a sheet of paper around a core at a fixed angle. This production method is called endless and the length of the tubes is determined by where the tubes are cut during the production process. Tubes that are created using the parallel winding method are more durable and their axis concurs with one of the main orthotropic directions of paper (MD or CD), which also makes it easier to describe their mechanical properties. Most paper tubes created using the spiral winding method have a winding angle between 10 and 30 degrees, depending on the inner diameter (ID) of the tube. A larger winding angle improves the fatigue strength of the tube, as the plies of the paper are positioned closer to the paper production direction (MD or CD). [40]

FIGURE 2.37 Paper tubes

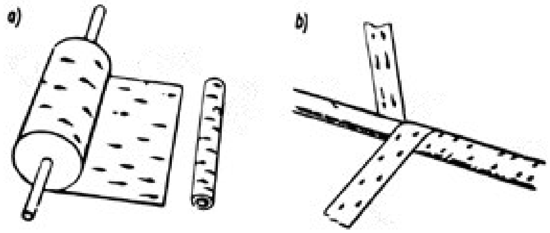

FIGURE 2.38 Two methods of paper tubes production a) parallel winding, b) spiral winding

The type of paper used for the production of tubes has thickness which generally ranges from 0.3mm to 1.2mm. [36]

Factors such as the quality of adhesive-bonded joints without air blisters between layers of paper have a significant impact on the mechanical properties of paper tubes. The properties of spiral winding tubes are determined by the angle at which the paper is wound and the presence or absence of breaks or overlapping layers of paper. Each subsequent layer should half overlap with the previous one. Using modern technology, spiral paper tubes can be produced with a speed as high as 160 m/min, but the speed depends on the winding angle. The number of laminated plies of paper may vary from 2 to 40. [36]

The most popular adhesive used by paper tube manufacturers is starch or PVA. However, certain types of tubes, such as the ones used as formwork, are laminated with cross-linked polyvinyl adhesive to make them more moisture-resistant. Another popular adhesive is liquid glass, but this type of lamination requires extra drying time, as well as the right conditions

When used as a part of a structure in architecture, paper tubes often undergo tensile forces parallel to the tube’s longitudinal axis and bending forces.

Tests measuring the compression strength of paper tubes are conducted using different methods.

In a flat crushing method tubes are installed between two parallel plates and are subjected to a load which is applied in a direction perpendicular to the longitudinal axis of the tube. Another test often conducted by the paper industry is the radial crush.

When subjected to axial compression, a tube may be pressed, locally buckled or globally buckled, depending on the diameter of the tube (see Fig.2.37).

Despite the viscoelastic character of fibre material like paper, it is possible to forgo taking into account the viscous characteristics and treat paper as an elastic material. This kind of simplification can be used during a short-term load tests involving forces that are far from destructive.

Another simplification used during paper tube testing is the assumption that paper tubes are homogeneous material without differentiating between the layers of paper and laminate. In such cases, Young's module might differ for axial and bending forces because of the orthotropic properties of paper. It is important to note that Young's module can be changed by layers made of different material (e.g. waterproof material applied to the inner- and outermost layers of a tube for impregnation purposes). [46]

When conducting laboratory tests, it is assumed that the paper tubes are made of elastic material. It is also assumed that sabsequent layers of paper are glued to the surface without any air bubbles and gaps and that the lamination is strong enough to withstand the whole strength test, which is to say that the delamination process will not start before the paper tubes are subjected to maximum forces. Moreover, it should be assumed that the climatic conditions in which the properties of paper were established are similar to the conditions under which the tests are conducted.

The paper tubes are tested in standard RH (relative humidity) and temperatures. The moisture content has a considerable impact the mechanical properties of paper. Significant strength reduction can be observed with increased moisture content above 7-8%, which is the typical moisture content in standard testing conditions at 21°C and 50% RH, and with sustained axial loading (creep rupture).

As Bank et al. report (2016), the flat and radial crush strength of paper tubes are both reduced by about 50 percent when the moisture content of the tubes increases from 5.5% to 13%. [39] Furthermore, the dimensional stability of the tubes changes depending on the moisture content. For every one-percent change in a tube’s moisture content, the length of the tube will change by 0.12% and its outside diameter will change by 0.09%.

As the properties of paper tubes can vary depending on the material used (i.e., the grade of paper) or on the winding angle and the diameter, both of which affect the mechanical properties of the tubes, it is common to test specimens before they are incorporated into a structure.

It is advisable to use 10-50% of the axial strength capacity when the tubes are under sustained long-term loads.

Connections – it is assumed that the total load on paper tubes is shared between screws in a connection.

Paper tubes are the most effective when they are used as a beams and columns in a small-scale framing system or small house-like structures.

The bending strength of paper tubes is approximately 40-70% higher than their compressive strength. The bending capacity of a tube can be enhanced by means of a thin layer of pultruded fibre-reinforced polymer.

Both parallel- and spiral-wound paper tubes were tested in the laboratory of Lodz University of Technology’s Institute of Papermaking and Polygraphy. In the early stages of loading, both types of tubes behaved like elastic material. The deformation graph is almost linear initially. Next, the deformation increases even if the load decreases. This is related to the viscoelastic and plastic properties of paper. If slim tubes are used global buckling can occur as well. During the tests, spiral-wound specimens were destroyed parallel to the direction of winding, whereas parallel-wound tubes were destroyed perpendicular to the axis of forces (see Fig.2.38). [4]

FIGURE 2.39 Paper tubes test on axial compression at TU Delft, noticable buckling

FIGURE 2.40 Paper tubes test on axial compression at TU Delft, wrinkles caused by axial compression

During the research for paper building of Westborough Primary School (see also section 4.3.8), BuroHappold determined that Yuong's module should be assumed to be 1 GPa and maximum compression force should be assumed to be 8.0-8.8 MPa.

It was also stated that paper is sensitive to atmospheric moisture and that a waterproof barrier is needed to prevent moisture from compromising the strength of the material. Furthermore, it was established that creep of paper tubes starts at 10% of the maximum compression level. Bending tests conducted at the University of Bath showed that paper tubes deform easily but with just a small amount of permanent deformation.

Compression tests conducted by BuroHappold showed limited endurance at 8.75 MPa. Tensile force tests showed that tensile and compression strength are similar, and that it is important to protect the connections at the ends of the tubes.

In order to minimise creep, a creep factor of 5 was established by BuroHappold and it was also established that the maximum long-term load should not exceed 1.6 MPa. BuroHappold also found out that paper tubes with a large diameter are weaker than paper tubes with a small diameter because their paper is wound at a greater angle relative to the tube axis. [40]

It is also important to take into account the angle at which the paper is wound to the core during the production of paper tubes. [42]

The book Shigeru Ban by Matilda McQuaid contains a great deal of information about stress tests conducted during the construction process of some of the Shigeru Ban's projects. [39] It includes information on the following buildings, whose structures were made of paper tubes:

1. Library of a Poet (tests carried out between August 1990 and August 1991)
2. Paper House (tests carried out between 14 October and 20 November 1991)
3. Paper Dome (tests carried out in July 1997)
4. Japan Pavilion at Expo 2000 in Hannover (tests carried out in November 1991).

In order to measure creep of the material, paper tube specimens with a length of 400mm were installed between two steel plates, which were fastened at 1000 kg (which was less than one-third of the maximum compression strength). The changes to the length of the tubes were measured for one year at one-week intervals. Temperatures and humidity levels were also measured at one-week intervals. The test results showed that the length of paper tubes is likely to undergo changes in wetter periods. The greatest change to the length of the tubes that was measured in the tests was 1.5-1.8mm (0.375% -0.45%) in a relative humidity of 80%. The tests showed that time played no role in the changing lengths of the tubes. This indicates that paper tubes are resistant to creep, if they are kept in hygroscopic equilibrium. Shigeru Ban confirmed this, telling the author of this dissertation that the dimensions of paper tubes may change in the first year of their being used, but that they stabilise after a while.

PROJECT	PAPER TUBE DIMENSION	MOISTURE CONTENT (%)	COMPRESSION STRENGTH (MPa)	AXIAL YOUNG'S MODULUS (GPa)	BENDING STRENGTH (MPa)	BENDING YOUNG MOD-ULUS (GPa)
Library of Poet	outer Ø 100, inner Ø 75 mm	-	10,12	1.82	-	-
Paper House	outer Ø 280, inner Ø 250 mm, length 600 mm	8,8	11,17	2.36	16,82	2,17
Paper Dome	outer Ø 291, inner Ø 250 mm, length 600 mm	10,0	9,74	2.07	14,9	2,11
Japan Pavilion	outer Ø 120, inner Ø 76 mm, length 240 mm	8,7	9,53	1,57	14,5	1,46

TABLE 2.4 Properties of paper tubes used in Shigeru Ban projects

Recommendations by BuroHapold on the mechanical properties paper tubes:

Maximum compression, tension and bending strength: 0.8 MPa adapted by a factor 0.1 for creep in relation to 8.1. The load at the attachment should not exceed 1.4 MPa. Maximum strength of adhesive for peeling: 0.3 MPa. Young's modulus 1-1.5 GPa. Monitoring of the material throughout its lifetime. [40,43]

During the realisation of the Paper House designed by Shigeru Ban, tests were carried out on five paper tubes, each with a length of 400mm. The tubes were tested using the three-point bearing method. When a tube was subjected to the maximum load, deformation was 124mm in the middle of the tube. The bending test resulted in the formation of diagonal wrinkles corresponding to the direction in which the paper is wound around the tube. They only appeared under compression (in the upper part of the tube).

Average strength for bending was 15.79 MPa, which is 1.42 of compression strength. Young's modulus was 2.18 GPa, which is equal to 92% of Young's modulus of compression. The average moisture content of the tubes was 8.9%. [41]

§ 2.7.3 Corrugated cardboard

Corrugated cardboard, also known as corrugated board or corrugated fibreboard, is the most popular material used in the packaging industry. Its production in Europe reached 43.4 million m2 in 2016, up 1.7% from 2015. [47]

Corrugated cardboard was invented and patented by two Englishmen, Edward Healey and Edward Allen, in 1856. The material was used as neat fluted paper used to line men's tall hats. In 1871 Albert L. Jones used corrugated cardboard for wrapping fragile items such as bottles. [48] A few years later, corrugated board with one side glued and both sides glued to a liner were patented in the United States. Corrugated cardboard was used as a material for packaging boxes since the early 1900s.

Corrugated cardboard is a sandwich composition of two flat layers of paper with a layer of corrugated medium (also known as fluting) in between (see Figs. 2.41 and 2.42). The layers are then laminated together. The thickness of the fluting can range from 0.8 mm to 4.8mm, and its grammage will be between 80 and 180 g/m2, while the liners have a grammage ranging from 115 to 350 g/m2. [49] The most popular types of paper used in the production of liners are Kraftliner (made of Kraft paper) and testliner (made of recycled paper). The corrugated medium (fluting) is made of recycled paper, which is also known as Wellenstoff paper, or of virgin paper, made using the semi-chemical pulping method.

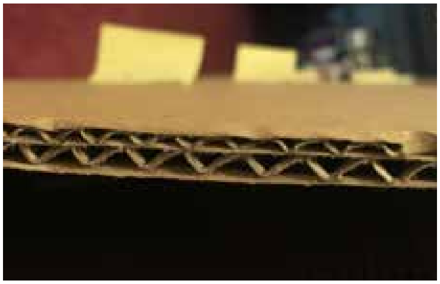

FIGURE 2.41 Double wall corrugated cardboard

FIGURE 2.42 Stack of corrugated cardbord plates

Corrugated cardboard is mainly produced for the packaging industry. The production of corrugated cardboard consists of three stages (see Fig. 2.43). First, the flutes are corrugated. Corrugation is obtained by pressing a sheet of paper at high temperatures, softening it by means of steam and forming by means of grooved metal rolls. The corrugation is created perpendicular to the Machine Direction of the paper. Next the outer liners are affixed with glue to one or both sides. Lastly, the laminated corrugated board is cut into the desired shape. The most popular adhesive in the production of corrugated board is starch, which, being a natural polymer, can be easily recycled. Special synthetic adhesives are used for water-resistant corrugated cardboard. The maximum size of corrugated cardboard is 2.40-3.25 metres wide and up to 5.0-6.20 metres long. [12]

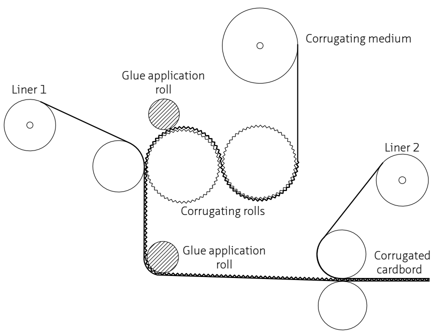

FIGURE 2.43 Corrugated cardboard production scheme

There are different types of corrugated cardboard, e.g. single-wall board (with a single corrugated medium and one or two liners), double-wall board (with two corrugated mediums and three linerboards) and triple-wall board (in which three corrugated mediums are alternated with four linerboards) (see Fig. 2.44). The most commonly produced type of corrugated cardboard is single-layered.

There are several types of corrugation. The smallest, type G, is less than 0.55mm high. The largest, type K, is over 5.0mm high. Corrugation height and pitch are the distances between two flute tips in the vertical and horizontal directions. The ratio of the length of uncorrugated material to the length of corrugated cardboard is called the take-up factor (see Table 2.5 and Fig. 2.45).

TYPE	HEIGHT [MM]	PITCH [MM]	TAKE-UP FACTOR
K	≥ 5.0	≥ 5.0	
A	4.0-4.9	8.0-9.5	≈ 1.5
C	3.1-3.9	6.8-7.9	≈ 1.45
B	2.2-3.0	5.5-6.5	≈ 1.4
D	1.9-2.1	3.8-4.8	≈ 1.5
E	1.0-1.8	3.0-3.5	≈ 1.25
F	0.6-0.9	1.9-2.6	≈ 1.25
G	≤ 0.55	≤ 1.8	≈ 1.25

TABLE 2.5 Types of corrugated cardboard

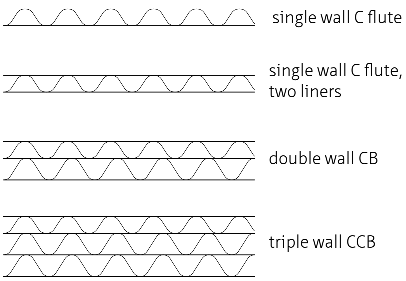

FIGURE 2.44 Types of corrugated cardboard

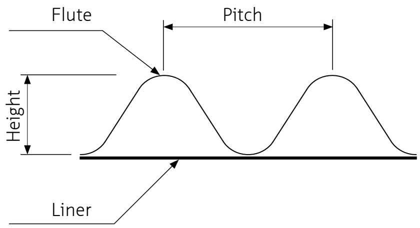

FIGURE 2.45 Dimensions of corrugation

The mechanical properties of corrugated cardboard depend on the material used for its production, as well as the type of corrugation.

The edgewise compression strength of corrugated cardboard is parallel to the axis of a corrugation and it is related to the type of paper used as well as to the geometry of the corrugation. The edgewise compression strength ranges from about 3 kN/m for single-wall board to more than 20 kN/m for double- or triple-wall corrugated boards. [13]

The bending stiffness is higher in the axis perpendicular to the axis of the corrugation and it comes from corrugated layers, while the stiffness in bending parallel to the axis of the corrugation comes from the liner layers. Increasing the corrugation size increases the bending stiffness due to the sandwich effect. The bending stiffness of corrugated board bent in the Machine Direction ranges from 3 Nm to 80 Nm. CD stiffness (i.e., the direction parallel to the corrugation) is about 50-70% of MD stiffness.

The in-plane shear resistance is higher in cross-machine direction than in machine direction. In the MD a lower ratio of the corrugation height to the corrugation pitch results in higher in-plane shear forces. Shear moduli for corrugated cardboard range between 1.8 MPa and 11.6 MPa in the MD, and between 11.2 MPa and 31.5 MPa in the CD.

Corrugated cardboard's high thermal performance is due to its structure, i.e. the liners, the layer of corrugation and the air kept between the layers. Its thermal resistance depends on the thermal conductivity of its components and the size of the corrugation. Larger cavities (higher waves) show higher thermal insulation properties. The thermal conductivity of corrugated cardboard at room temperature ranges from 0.29 W/mK for small corrugations to 0.045 W/mK for bigger corrugations (e.g. Type A, B or C).

§ 2.7.4 Honeycomb panels

Honeycomb panels are low-density, cellular sandwich panels (see Fig. 2.46). They are made up of three layers: two facings and one core layer, which have a honeycomb-like structure (see Fig. 2.47). The panels can be made from paper or other materials such as fibreboard, plywood, aluminium , resins, or other metals and polymers. Honeycomb panels were introduced to the industry in the early 1900s. Since that time their application has become widespread in different industries, including construction and furniture production. [50] During World War II, research on this high-strength and light-weight material was accelerated by the aviation industry.

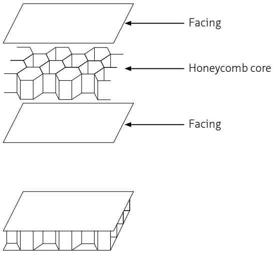

FIGURE 2.46 Honeycomb panel sandwich structure

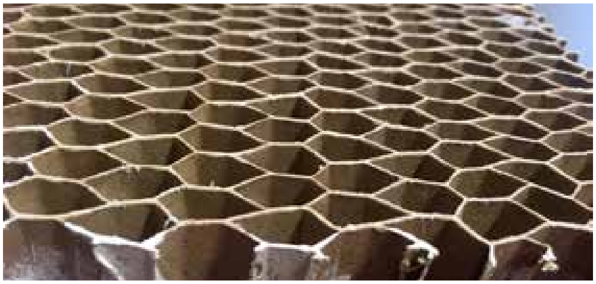

FIGURE 2.47 Honeycomb panel core

Honeycomb panels are often used in furniture, mainly as a filler of tabletops and shelves. They are also a material commonly used as door fillers. In the packaging industry, honeycomb panels, being bio-degradable materials, have come to replace foam products used as inner packaging. They are also used in the automotive industry, as sandwich panels composed of cardboard honeycomb core and finishing layers made of glass fibres or natural fibres.

Cardboard honeycomb panels are produced in two steps. First the honeycomb core is prepared. Then it is laminated to the facings.

In a traditional production process, the honeycomb core is produced by the lamination of sheets of paper by means of glue lines printed on flat sheets (see Fig. 2.48). Then the sheets are stacked on top of each other. After the glue has cured, the block of paper sheets is sliced. Lastly, the slices are pulled apart, thus expanding into a hexagonal honeycomb core. The residual stress in paper honeycombs is relaxed after expansion by heat. [51]

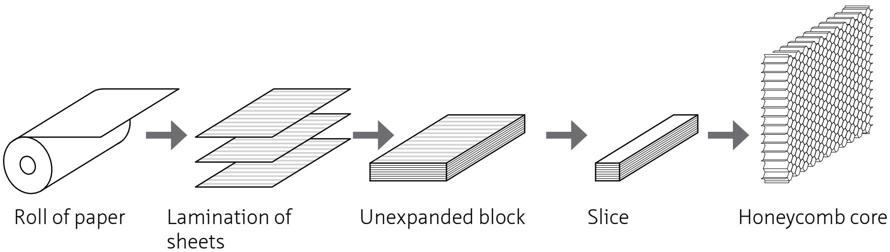

FIGURE 2.48 Honeycomb core traditional production method

The second method, also called the corrugated honeycomb core production process, uses corrugated cardboard sheets, which are first glued to each other, then sliced and expanded (see Fig. 2.49) The second process results in smaller cells, depending on the type of flute used, and is cheaper.

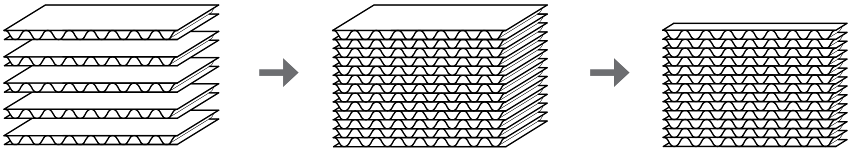

FIGURE 2.49 Honeycomb core production from corrugated cardboard

The size of the honeycomb panels produced as outlined above depends on the dimensions of the liner paper, which are typically 1,200mm. The length depends on the length of the machine, and typically reaches 24,000 mm. The height of the panels varies from 8 to 100mm.

The most popular type of paper for used for the production of panels is Kraft or recycled paper with a grammage between 140 g/m² and 300 g/m².

Honeycomb panels are characterised by high compression strength in the Z-direction, i.e. perpendicular to the surface, which may be as high as 100 kN/m². [44]

§ 2.7.5 U- and L- shapes

Cardboard U- and L-profiles consist of several layers of paper pressed into shape, laminated and covered with a finishing layer, which can be coloured, high gloss or printed (see Fig. 2.51). Layers of paper, which can be as heavy as 450 g/m² and 0.7mm thick, are laminated with water-based liquid adhesive. The flanges (A and B) can be between 35 and 100mm and can have a thickness (T) of 2 to 10mm (see Fig. 2.50). Profiles are produced in lengths (L) ranging from 50 millimetres to 10 metres. Profiles are used primarily for transportation purposes, as a means to protect the edges of goods being transported, e.g. books or furniture. [52]

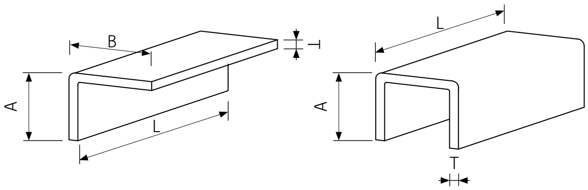

FIGURE 2.50 L- and U- shapes dimensions

FIGURE 2.51 Cardboard beam made from two laminated U-shapes

Tests conducted at TU Delft showed that the compression strength of profiles made out of recycled cardboard was as high as 8.53 MPa. Their Young's modulus was 1.28 GPa (also see the Appendix).

§ 2.7.6 Other paper-based products

Currently there are many other paper-based products which can be used in design and architecture.

Nanopaper consists of cellulose fibrils that have been reduced to nanometre size. In its production process wood cells are dissolved and refined. This smaller particles display better adhesive properties and create more homogenous paper with cavities, which increase the product's resilience. This extremely tear-resistant material is produced without any additives, so the fundamentals are the same as in normal paper.

Vulcanised paper is produced by bathing sheets of paper in zinc chloride, which turns the surface of the paper rubbery and sticky. Then the paper sheets are pressed together and the zinc chloride is rinsed away. Vulcanised paper is water-resistant, very strong and durable and does not contain any additives such as glues, binding agents or resins. This type of paper was traditionally used for the production of armour for Japanese sword fighters. It can be used as a light-weight structural element.

Transparent construction panels are made out of cellulose acetate. Transparent cellulose made of pure cellulose is produced by dissolving pulp in soda and carbon disulphide.

‘Monifex’ are the honeycomb-shaped, light-weight and air-permeable panels produced by Isoflex. [53]

Kraftplex is a panel containing pure cellulose. Its material and shaping properties are similar to those of metals and plastics. Kraftplex is made of softwood fibres by a German company called Well, which only uses water pressure and heat during the production process, without any chemical additives, bleach or adhesives. [54]

Pressed cellulose panels are produced out of paper sheets, which are pressed together under high temperatures and great pressure. During this process the cellulose coalesces into a rigid substance. [54]

Ceramic paper is a product developed by PTS, a German research organisation that works for the paper industry. During the production process, standard paper is enriched by means of aluminium, silicon powder and latex. The paper can be shaped and folded like typical paper. However, it is then processed at a temperature of 1,600°C, after which the paper ingredients are burned away, which results in a concentrated and solid object. This product is characterised by a good resilience to pressure, chemicals and high temperatures. [55]

Fire-resistant paper (produced by a German company called Additherm Group) is manufactured by adding seed crystals to the pulp. During the drying process a chemical bond is created between the crystal matrix and the cellulose fibre matrix. Several types of products can be manufactured by using this technology, such as laminated cardboard, paper foam and paper-insulating boards. The AddiTherm Stop Steel Coating is a cellulose-based product that is used as a fire-prevention coating for steel beams. [52]

In association with Shigeru Ban, company UPM-Kymmene, a company working with the foresting industry, developed a new paper-based material for the construction of an exhibition pavilion for a furniture-making company called Artek. The material consists of waste paper which is chaffed and extruded into L-shaped profiles. The product only contains recycled adhesive labels without any plastic or adhesives. UPM-Kymmene now produces UPM ProFi Deck outdoor flooring boards, based on this product.

The ‘Paper brick’ is an invention by WooJai Lee, a Korean-Kiwi designer based in Eindhoven, the Netherlands. ‘Paper bricks’ are made of recycled newspapers, which are pulped, mixed with glue and shaped into bricks. In the words of the designer, ‘Sturdy as real bricks, they combine a pleasing marbled look with the warmth and soft tactility of paper. When you touch the ‘Paper bricks’, you can feel the soft textile-like texture’ (see Figs. 2.52 and 2.53). [56]

FIGURE 2.52 'Paper brick'furniture

FIGURE 2.53 Structure of the 'Paper brick'

§ 2.7.7 The paper industry and its future

It seems that the golden era of paper-making may be about to end. According to statistics provided by CEPI (the Confederation of European Paper Industries), Europe's paper production capacity decreased by 12 percent in the years 2005-2013. The production of pulp mass decreased by 10 percent, while the production of paper and cardboard fell by 7%. The production of printing paper has especially decreased. Modern information media, such as the Internet and e-books, have recently contributed to a considerable decrease in newspapers' circulation and newsprint production. At present, entrepreneurs of the paper industry are not investing in the development of machines producing newsprint and other types of printing paper. Rather they are focusing on reducing the amount of printing paper they produce. In addition, they seek to strengthen the paper-making sector by producing packaging paper and packaging materials, paper-based filling materials used in transport, and particularly mass-produced boxes made of corrugated board. They also produce more niche products such as shaft cores, or highly advanced paper products with a honeycomb structure, which are perfect structures observed in nature, distinguished for their high efficiency and minimal use of material, and therefore material-efficient and very light.

We can support the paper industry by looking for new ways of using not only paper, but all sorts of renewable, inexhaustible plant material, which can be used to produce the aforementioned elements by means of paper-making methods. Paper- and cellulose-based materials and products have great potential for use in architectonic design, in the broadest sense of these words. Paper elements can be successfully used in furniture, industrial design and small architectonic forms, as well as in architecture.

Contemporary trends in architecture are centred around environmentally friendly solutions that make use of renewable and eco-friendly materials and have a low built-in energy factor (kJ/kg) – in other words, materials whose production and processing are simple and energy-saving.

Great significance is attached to the whole life cycle of a building, which consists of three stages: construction, use and demolition.

What is essential is that a building material should only have the slightest possible impact on the natural environment after its demolition.

§ 2.8 Conclusions

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 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. 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 [4, 14, 15].

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.

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.

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.

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.

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 and pulping method used. 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.

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

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.

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.

Developing and using functional and sustainable paper requires creativity and open-minded approach from researcher, industry and marketing.

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3 Paper in design and architecture. Typology

The whisper of paper is deep
and when our feelings are intensive,
that voice cannot be heard.

Mitsuhiro Ban, 'Handbook on the Art of Washi' [1]

§ 3.1 Introduction

Paper base products such as corrugated cardboard, paper tubes, honeycomb panels and strong papers like Kraft and Washi can be successfully used for the production of interior design, products for everyday use, furniture, indoor partitions, pavilions and bigger architectural structures. Paper and its derivatives are often used for other purposes such as educational (origami) or social and artistic events.

Moreover, paper and cardboard are cheap and eco-friendly materials. Therefore, are they fit to be used in spatial structures for a limited lifespan. Fairs, exhibitions, major sporting events and other short-term events cost an enormous amount of money, and in many cases leave behind an ecological burden in the form of construction waste.

In 2008, under the EU's revised Waste Framework Directive, a new target for recycling rates was established. By the year 2020 50% of municipal waste, including at least 50% of paper, metal, plastics and glass, will have to be recyclable, as well as 70% of demolition waste. [2]

The projects presented in this chapter are characterised by different size, geometry, materials and properties, as well as by different connections between these aspects. The projects were created by various designers, including the author of this thesis.

In this chapter, the typology of paper and cardboard in design and architecture is described and depicted by means of realised examples. Smaller projects of the first two types are described below, in this chapter. For their part, more complicated structures, such as large pavilions, houses and public buildings, will be described in Chapter 4. Emergency and relief projects will be presented in Chapter 5.

§ 3.2 Typology

The history of paper spans almost 2,000 years in Eastern civilisations. It has been almost 500 years since paper was first used in Europe for architectural applications, in the form of wallpaper, which was probably invented in Persia. [3] Cardboard and paper have been used as a structural material for about 150 years, which allows us to make certain observations about the specific features of the projects that have been realised. Five functional categories can be distinguished with regard to the level of complexity, size, material composition, budget and lifespan of the projects:

- **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, scenography, 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 lifespan of such buildings is estimated to be between twenty years and fifty years.
- **Public buildings** such as schools, universities, sport clubs and galleries. Such structures are built to last for twenty years or permanently.
- **Emergency and relief architecture**, intended for people who have lost their houses due to poverty, social exclusion, natural disasters and human-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 sizes of S, M, L, XL were established by means of conducted research on the 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 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 involves projects such as furniture and interior design elements, indoor partitions and screens, industrial design and art compositions. 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 and production. This category encompasses housing structures, major art installations, exhibition pavilions, etc. Such structures are mainly composed of cardboard elements and the other materials used for connections between the elements. Important factors are impregnation and connection with the gound. 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 mounted on the building site. The buildings in this category have a size between 50 and 450m^2. They require a large financial outlay for material research, experiments and tests, building the prototypes and expert consulting. Their assembly requires specialised 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 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, building material composition, 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 involve various fields of science and industry. Projects in this category cover an area greater than 450m^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.

§ 3.3 Furniture, interior and industrial design, arts and crafts and products for everyday use

This section presents furniture, interior and design projects, arts and crafts, and products for everyday use. The objects presented in this section fall into the Small-size category.

The oldest products in this category are screens made out of paper stretched on a timber lattice, produced in ancient China, Korea and Japan (see Fig.3.1). The oldest remaining references to such products are from the eighth century AD. [4] Aside from screens, typical products made out of paper include decorative origami compositions, kusudama (spherical origami objects containing aromatic substances), lamps (see Fig. 3.2), umbrellas or clothes made of woven threads produced from twisted stripes of washi paper (see Fig.3.3).

FIGURE 3.1 Traditional Japanese screen, produced in Kyoto, 2013

FIGURE 3.2 Traditional Japanese paper lamp, Kyoto, 2013

FIGURE 3.3 Traditional cloth made out of washi paper, Echizen, Japan, 2013

These days, in addition to packaging, decorations and paper art, products in this category tend to be furniture and elements of interior design, industrial products and cloth made out of paper or viscose (chemically processed cellulose). [5]

§ 3.3.1 Arts and crafts; interior design elements

The products presented below are the smallest products from the interior and industrial design category.

In 2008, Japanese fashion designer Issey Miyake designed a collection called ‘Pleated Paper Dresses’. The premise for the collection was the conviction that in approximately fifty years, the only accessible fibre will be cellulose fibre. After several months’ worth of research on different materials and their processing, the designer and his team presented a collection of dresses made out of packaging material which was formed and folded into the desired shapes (see Fig.3.4). Issey Miyake’s fashion designs are characterised by great attention to details and modesty of form and material, as well as accents, which is typical for Japanese design. [6]

Another Japanese company, SIWA, produces everyday objects made out of specially processed washi paper. Naoto Fukasawa designs bags, phone and laptop cases, wallets, etc. made out of paper made up of wood cellulose fibres and polyolefin, in accordance with the tradition of *washi-suki* paper. The material is tear-resistant and watertight. The ONAO company, which produces the paper from which the objects are made, has more than one thousand years’ experience of paper production. One characteristic ingredient of the products is *wabi-sabi*, a Japanese philosophy of aesthetics that finds beauty in imperfect and ephemeral objects and beings (see Fig. 3.5). [7]

As part of the scientific students’ organisation Humanisation of the Urban Environment, Aleksandra Omiotek, Mikolaj Romanowicz, Joanna Zyłowska and the author of this thesis in 2011 created the UL Lamp for commercial spaces, pubs and restaurants. The lamp was created in accordance with the tenet of the organization, i.e., human-environment-friendly design. The lamp was made of two honeycomb panels core with a thickness of 30mm, which were formed while being soaked and next dried and impregnated with timber varnish (see Fig. 3.6). The shape of the lamp was created by several pairs of hands shaping the panels. Thanks to the cell structure of the material, the lamp glows with soft light.

FIGURE 3.4 Pleated paper dress, author Issey Miyake, 2008

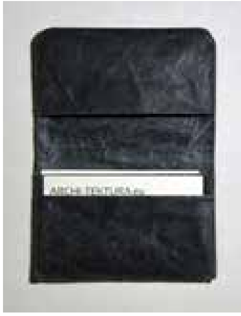

FIGURE 3.5 Business card case made out of processed washi paper, SIWA

FIGURE 3.6 UL Lamp designed by Jerzy Latka, Aleksandra Omiotek, Mikolaj Romanowicz and Joanna Zylowska, 2012

§ 3.3.2 Furniture

Furniture makes up the largest group of paper-based products on the market. The projects presented here were chosen on the basis of the diversity of the materials used and their composition and characteristics.

The most popular pieces of furniture made of cardboard are the chairs from the Easy Edges series, especially Wiggle Side Chair (see Fig. 3.7), designed around 1970 by American architect Frank O. Gehry. The series of chairs and lounges was made out of corrugated cardboard profiles laminated to each other with alternation of the corrugation at an angle of 90°, in order to make the composition more stable. The sides of the chairs were protected by hardboard. The Easy Edges chairs became a great success, especially at a time when paper and cardboard were increasingly being edged out by lightweight plastics. However, Gehry decided to discontinue his furniture designs and to focus on architecture instead. Since 1986, the Swiss company VITRA has produced selected models of the Easy Edges series.

Another example of interior design created by a well-known architect is the Carta Collection designed by Japanese architect Shigeru Ban. The collection was initially designed in 1994 for the Miyake Design Studio Gallery in Shibuya, Tokyo. The collection was later expanded to include a chair, chaise longue, screen and table (see Fig. 3.8). The architect used impregnated paper tubes connected with timber elements. The pieces of furniture making up the Carta Collection are produced by Swiss company wb form. [8, 9] Through his large number of projects from many categories and in many sizes, Shigeru Ban drew people's attention to paper and cardboard as a contemporary building material.

FIGURE 3.7 Wiggle Side Chair, Frank Gehry, 1972

FIGURE 3.8 Chair, Shigeru Ban, 1994

Apart from well-known architects, many other designers have tried to use paper and cardboard, especially recycled paper and cardboard, in order to create interior and industrial design products.

The American designer Zach Rotholz, an alumnus of the Faculty of Mechanical Engineering at Yale University and founder and CEO of Chairigami (the name is derived from 'chair' and 'origami'), designs and produces furniture composed of triple-wall corrugated cardboard. The material for his designs consists of 70% recycled fibres and 30% virgin fibres. Chairigami's collection includes chairs, tables and shelves. All its products consist of flat plates of cardboard which are folded by the customer. Their assembly does not require any additional materials, glue or joining elements (see Fig. 3.9). Chairgami's products are much more affordable than the pieces of furniture designed by the famous architects [10].

Australian company Karton Group [11] designs, produces and sells furniture made out of recycled cardboard. The company produces chairs, tables, shelves and beds, which can be folded into shape by users within five minutes. [12] The elements of the cardboard bed are pre-folded, then inserted into each other. Their ribbed structure is reminiscent of the lightweight structures used for the construction of aeroplanes. The carrying capacity of Karton's cardboard bed, made of mixed recycled and fresh fibres, is 2,000 kg (see Fig. 3.10).

Swiss architect and designer Nicola Stäubli created a non-profit line of furniture for children, intended to be built by the future users themselves. Free patterns can be downloaded from his website (www.foldschool.com) and used to cut the shape of the furniture, which can then be folded into the right form. The assembly of the furniture requires nothing but basic and readily available tools such as scissors, spray glue, cutting mats, etc. The concept of the foldschool is based on the sustainable play with recycled material. The original products were made out of 4mm corrugated cardboard (see Fig. 3.11). [13]

FIGURE 3.9 Lounge Chair, Zach Rotholz, 2011

FIGURE 3.10 The Paperpedic Bed, Karton Group

FIGURE 3.11 Foldschool, Nicola Stäubli, 2007

§ 3.3.3 Furniture by the Humanisation of the Urban Environment Design Team

This line of furniture made of paper-based materials was designed and produced by the author of this dissertation, in collaboration with students of the Humanisation of the Urban Environment Science Organisation from Wroclaw University of Science and Technology's Faculty of Architecture. The furniture was presented at the Home(less) ness exhibition at the Wroclaw Contemporary Museum in May 2012 (see Fig. 3.12). [14] The authors of the exhibited pieces were Jerzy Latka, Małgorzata Bienkowska, Mariusz Biernacki, Katarzyna Drapa, Anna Jakubinska, Aleksandra Omiotek, Karol

Madrecki, Alicja Sawicka, Justyna Sielska, Katarzyna Starzak, Mikołaj Romanowicz and Joanna Zyłowska.

FIGURE 3.12 Collection of chairs and lamps. Home(less)ness exhibition, Wroclaw Contemporary Museum, 2012

The materials used to construct the furniture were mostly corrugated cardboard, honeycomb panels and paper tubes. These products were combined with other materials, such as wood, metal and Plexiglas.

The MCT (Modern Christmas Tree) Lamp was made out of a paper tube with a length of 2000mm, diameter of 100mm and walls 4mm thick. Holes were drilled into the tube using differently-sized drills in order to allow the light from the bulbs or LED stripes placed inside the tube to shine outwards (see Fig. 3.13). The name of the lamp refers to the authors' idea that a pro-ecological material be used for lighting rather than a real Christmas tree that needs to be cut from the woods.

Another piece made out of paper tubes was the La-Ma Table. Connected tubes were put together and laminated in such a way that they would serve as a table while at the same time serving as a storage place for the paper cups used during the vernissage of the exhibition (see Fig. 3.14). Part of the table is covered with Plexiglas. The paper tubes used in the project were 70mm in diameter, and their walls were 4mm thick.

FIGURE 3.13 MCT Lamp and Muff Puff seats

FIGURE 3.14 La-Ma Table

The Muff Puff collection is a line of seats whose shape is reminiscent of muffins or cupcakes. The seats are made of paper tubes with a diameter of 470mm and wall thickness of 7mm produced by company Mawocores [15]. Cushions or poufs are placed at the top of the paper tube. The space inside the paper tube can be used for storage purposes (see Fig. 3.15). The same collection also contains a sofa that is a reference to a classical piece of design called the Marshmallow Sofa, designed in the 1950s by Irving Harper and George Nelson. [16] Unlike the original design, the parts of the Muff Puff Sofa (sliced paper tubes and cushions on the seat and at the back) were made out of recycled materials. The cushions are inserted into the sliced paper tubes. For this reason, the furniture can be customised colour-wise. The structure of the Muff Puff Sofa is made out of 72mm thick plywood and 3mm thick steel wire (see Fig. 3.16).

FIGURE 3.15 Muff Puff Seats

FIGURE 3.16 Muff Puff Seats

The Patchwork Armchair was made out of honeycomb panels with a thickness of 25mm and square cushions made out of recycled materials. The side case of the armchair can be used as a worktop and storage space for books, magazines or simply a cup of coffee. It also plays a structural role, enhancing the stability of the whole armchair (see Fig. 3.17).

The Rocking Chair Massager is a piece of furniture that combines paper tubes with timber. Horizontally placed paper tubes are attached to the sides of the chair, which are made of plywood. They serve as a seat, but at the same time they can be used as a shelf for books or newspapers, which can be reached from the back (see Fig. 3.18).

FIGURE 3.17 Patchwork Armchair

FIGURE 3.18 Rocking Chair Massager

Lounge L was an attempt to create a piece of furniture for temporary use. It consists of honeycomb panels that were inserted into one another by means of pre-cut slots. The Lounge was assembled within several seconds from elements taken from a box whose dimensions were 1.5x1.5m and which was 200mm thick. The idea behind the Lounge was to create a piece of furniture which can be easily stored and transported and quickly assembled and disassembled when necessary (see Fig. 3.19).

The exhibition also featured another seat made of honeycomb panels: Kart®on, a high-backed chair designed for a dining room. It was made of twenty honeycomb panels, each of which was 25mm thick. The panels were first cut into the desired shape, then laminated together (see Fig. 3.20).

FIGURE 3.19 Lounge L

FIGURE 3.20 Kart®on chair

§ 3.3.4 Work&Chill furniture

The participants of the 2017 Summer School of Architecture, Work&Chill, organised by the author of this thesis, were asked to draw up projects and later to build prototypes of multi-functional furniture made out of cardboard and other materials. The Summer School, organised at Wroclaw University of Science and Technology in association with TU Delft, was a course that went beyond the core of the curriculum at the two universities' Faculties of Architecture. During the Summer School, students were challenged to design and build multi-functional units that could serve as a place where people could relax, work and have meetings.

Open spaces, school corridors, universities, factories and other work places often lack social areas, where employees or students can meet, talk, relax or even work in groups or undertake other actions. Since we spend at least one-third of our lives in a work environment, we need spots that will turn this environment into something pleasant, close to its users, something that will make the workplace feel more like a home.

The theme of the 2017 Summer School of Architecture, 'Work&Chill', referred to innovative, mobile, usable, modular, comfortable and affordable solutions that will meet the demand for social spots in the workplace, thus making workplaces more homely and user-friendly.

Work&Chill refers to a spot where one can sit, lie, relax, talk with friends, work in groups or alone, study, read and engage in all the other activities that are expected in workplaces like offices, schools, universities and factories. Workshops were taught for 2.5 weeks, during which time 26 architecture students, supervised by Dr Marcel Bilow and Jerzy Latka, constructed five Work&Chill spots. Four groups used paper as the main building material, while one group mainly used timber. The projects realised during the workshops included the following:

Cardboard:ception (authors: Marcin Dudkowski, Monika Kalinowska, Piotr Panczyk, Natalia Rod and Agata Wycislok) is a project realised for Wroclaw Contemporary Museum. Cardboard:ception is a multi-functional installation, which was placed under the staircase in the Museum (see Fig. 3.21). The context posed some problems to the students. Wroclaw Contemporary Museum is situated in a former bunker and its functional lay-out is concentric, meaning that all the walls, corridors and rooms are curved. The project, in the form of a special grid, follows the wall's curvature and creates a cosy nook for book-crossing, reading and waiting. There are modular seats on cases next to the books, and the whole structure has empty spaces filled with cushions in which people can seat or lie.

FIGURE 3.21 Cardboard:ception

FIGURE 3.22 Landscape bench

Landscape Bench (authors: Gabriela Barlik, Bartlomiej Bienkiewicz, Jozefina Furmanczyk, Dominika Piecuch, Margareta Sztejkowska, Paulina Urbanik, Przemyslaw Wdowiak and Paula Werblicka) is a bench and seat inspired the landform with canyon. The product was made from layered honeycomb panels and finished with wood. It was designed to serve as a reception desk or space for relaxation and work in open spaces such as offices or library lobbies (see Fig. 3.22).

Work&Roll (authors: Szymon Ciupinski, Anna Domagala, Andrzej Kaczmarek and Paulina Lechowska) is a mobile, revolving module whose multi-functionality is achieved by rolling the module into a different position. This octagon-shaped piece of furniture has an empty interior in the form of soft and organic planes which, depending on the position, can serve as a lounge, seat with table or chair. Work&Roll can be used for both work and relaxation, in a dozen different positions. Paper makes up about 90% of the product. Thirty-two layers of honeycomb panels were laminated together and protected from the outside with plywood (see Figs. 3.23 and 3.24).

FIGURE 3.23 Work&Roll

FIGURE 3.24 Work&Roll – detail

§ 3.3.5 Space dividers and partition walls

Today there are many products on the market that function as interior partition walls, screens or space dividers. Many of these products are made of paper, cardboard and other materials, including textiles.

The prototype of Paper Miracle, a third-prize-winning competition project, was presented at the Home(less)ness exhibition at the Wroclaw Contemporary Museum. The competition challenge was to design a space for creative meetings within office spaces. The Paper Miracle was designed by the members of the Humanisation of the Urban Environment Scientific Organisation: Anna Jakubinska, Katarzyna Laskowska and Jerzy Latka. The aim of the design was to create a system consisting of one type of main module and one supportive module. By combining the modular elements together like 3D puzzles, the division of the space and room for creative activities was created. To get office workers' creative juices flowing, the employees were obliged to build the structure themselves, which could be done according to patterns and manuals provided, or in any way the employees themselves came up with (see Fig. 3.25). The other important factor was team work, which was required both in the visionary stage and at the execution stage. The modular elements were made out of honeycomb panels with a thickness of 30mm and dimensions of 450x450mm (main element) or 450x270mm (secondary element). The panels were made of recycled material and were able to be recycled after the lifespan of the piece of furniture. The proposed system was relatively cheap and therefore affordable to almost everyone. Because the modular elements were so cheap, they could be used in different ways. They could be covered in notes, painted and replaced. New parts could be built and existing structures could be expanded, thus creating simple furniture. The destruction of the elements could even get people's creative juices flowing (see Figs. 3.26-3.28).

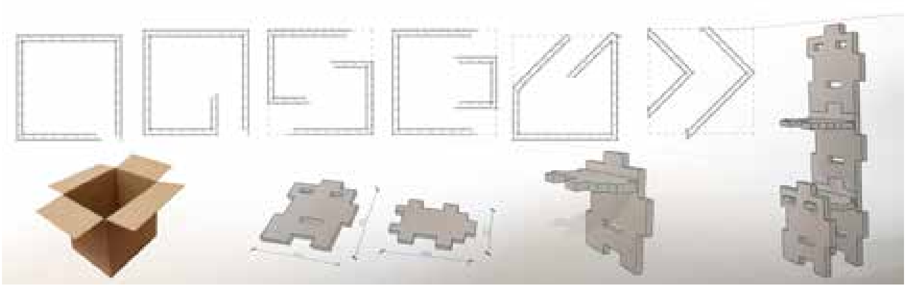

FIGURE 3.25 Paper Miracle – proposed patterns of the space and single modular elements, 2011

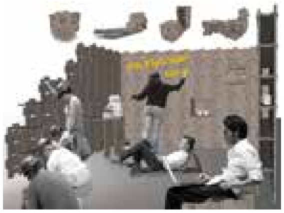

FIGURE 3.26 Creating Paper Miracle, 2011

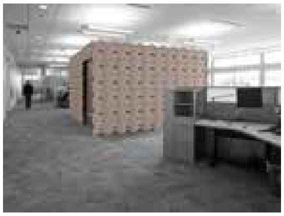

FIGURE 3.27 Paper Miracle structure in the office space, 2011

FIGURE 3.28 Paper Miracle, 1:1 prototype exhibited at Wroclaw Contemporary Museum, 2011

Nomad System Room Dividers was created by American designers Jaimy Salm and Roger Allen. The company's room dividers consist of modular elements cut from corrugated cardboard. The material used is craft paper, 30% of whose fibres are recycled. Rounded rectangles with incisions can be covered with patterns or colors printed on their surface (see Fig. 3.29). Each of the modules has a dimension of 530x355mm and a thickness of 5mm. The demountable lightweight structure of the partition wall is assembled by inserting elements into the incisions of the adjacent elements. The Nomad System is produced by a company called MIO. Apart from the Nomad System, MIO offers a variety of products made of cardboard and paper, including partitions, acoustic tiles and decors. [17]

Bloxes is a concept that uses the art of folding flat cardboard into three-dimensional elements. The name of this cardboard-based modular system is derived from the combination of two words: 'block' and 'boxes'. The basic material is corrugated cardboard. Each folded module has a side dimension of 240mm. The project can be compared to Lego blocks. Each of the folded modules is shaped like a small cube with flaps which allow it to be connected to the next module (see Fig. 3.30). The Bloxes can be used to create partition walls and simple pieces of furniture like seats or tables. Bloxes were invented by American Jef Raskin in the late 19060s. In 2008 his son, Aza Raskin, patented the Bloxes. He is currently working on their development in association with Andrew Wilson. [18]

BIA Systeemwanden is a Dutch producer of prefabricated partition walls consisting of three layers. Depending on the model, the outer layers can be made of gypsum, Farmacell boards (a mixture of gypsum and cellulose fibres) or 4mm paperboard. The inner layer is made of corrugated cardboard which fills the gap between the outer layers in a zig-zag-like pattern. Due to the use of the corrugated cardboard infill, the lightweight partitions become more stable. The prefabricated elements are assembled on wooden slats and if necessary are caped form the top with a U-shaped bar. The two adjacent panels are held together by clips made of metal or cardboard (see Fig. 3.31). In order to make T-like or corner connections, BIA Systeemwanden created special corner elements filled with honeycomb panels. BIA Systeemwanden can be used in both residential and commercial spaces. [19]

FIGURE 3.29 Nomad System Room Dividers, 2016

FIGURE 3.30 Bloxes – prototype from the 1960s

FIGURE 3.31 BIA Systeemwanden, 2015

The Canadian design company Molo created a line of elastic space dividers called the softwall + softblock modular system. The collection, designed by Stephanie Forsythe and Todd MacAllen, also includes seating (soft seating) and tables (a cantilevered table) (see Fig. 3.32). All the products have one thing in common: they are made of material that has a honeycomb-like structure, so it is elastic and can be stretched, shortened and formed according to one's own idea (see Fig. 3.33). Some of Molo's products are made of Kraft paper, 50% of whose material was recycled, with the remaining 50% being virgin cellulose fibres. The products are fire-retardant. However, after being used, they can still be recycled. The softwall in folded state has a thickness of 50mm, so it can be easily transported and stored. Once unfolded, the softwall can be extended several dozen times, to a length of 4.5m. The width of the softwall is 305mm. The maximum load on the 305mm softwall section is 15.5 kg. At the ends of the partitions there are panels with magnets, which can be used to attach the sections of the walls to the next module of the partition. Furthermore, the package contains hooks which can be mounted to an existing wall so that the folded softwall or softblock can be hung from them. The maximum height of the partition is 3m. Since 2008 the soft collection has been part of a permanent exhibition at the Museum of Modern Art in New York. [20-22]

FIGURE 3.32 softblock and softseating, molo, 2003

FIGURE 3.33 The honeycomb structure of the softwall, molo, 2003

Interior partitioning was one of the themes explored by the Cardboard in Architecture scientific design team, which was established at TU Delft's Faculty of Architecture and the Built Environment in the years 2003-2008. [23] One of the challenges faced by the members of the team was to create and research a system of partition walls made out of cardboard. Taco van Iersel and Elise van Dooren conducted the research and analyses of three types of partition walls made out of cardboard whose structure corresponded to that used in traditional building techniques. The technical specifications were influenced by three types of associated factors: legislation (fire-retardant cover, thermal insulation, acoustics), user demands (transportation, assembly and disassembly) and economics (the market). Having researched various commercially available forms of partition walls and building materials, the group distinguished three basic archetypes of internal partition systems:

- **Hollow wall system** – consists of posts and cross beams with plating (see Fig. 3.34). In this system, the cavity inside the wall can be used as a space for electrical wiring and acoustic and thermal insulation materials. In the solution proposed by the researchers, a wooden frame was covered with material used for the production of packaging for liquids such as Tetra Pack boxes. The packaging for liquids consists of layers of paperboard, polyethylene and aluminium. The air cavity was 20mm, creating air thermal insulation, and the aluminium in the packaging layer reflected heat from radiation. However, in order to achieve the same kinds of results as hollow wall systems currently available in the market, many layers of packaging material would need to be applied, which would result in additional work and high costs.

- **Stacking system** – which can be sub-divided into two types of systems: load-bearing (sand-lime blocks) and not load-bearing (i.e., aerated concrete). The alternative solution the team came up with was cardboard bricks connected to each other and to the layer underneath by means of flaps and glue (see Fig. 3.35). This solution is a modern take on good old-fashioned masonry, but at the same time, it is much lighter and less durable. The main problem was the need for glue to connect the cardboard bricks, which significantly increased the time needed for construction.

- **Panel system** – consists of prefabricated wall panels which were connected to each other (see Fig. 3.36). This system is characterised by the limited time required to build it, the minimal number of actions required on the building site and high flexibility. However, there is a limiting factor, which is the weight of the panels. According to the Dutch building code, the maximum weight which can be carried by one person is 25 kg. The cardboard alternative to this system consisted of honeycomb panels with a liner made of paperboard. The profiled edges were H-shaped. The assembly process was dry, which means it did not require any adhesives. The panels could be recycled after demolition.

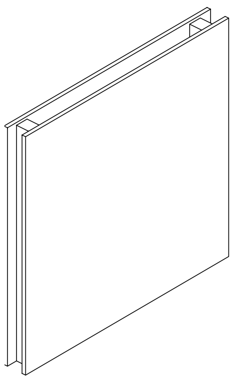

FIGURE 3.34 hollow partition system

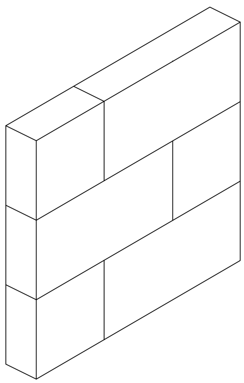

FIGURE 3.35 stacking partition system

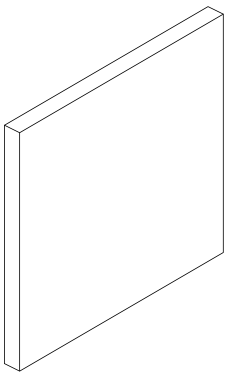

FIGURE 3.36 panel partition system

The scientists from TU Delft compared three types of material (cardboard, wood and sand limestone) used for the production of one metre square of partition wall with regard to environmental burdens, resources, amount of energy and water used for production, weight and potential for disassembly and recycling. Please find the results of the comparison below (see Tab.3.1):

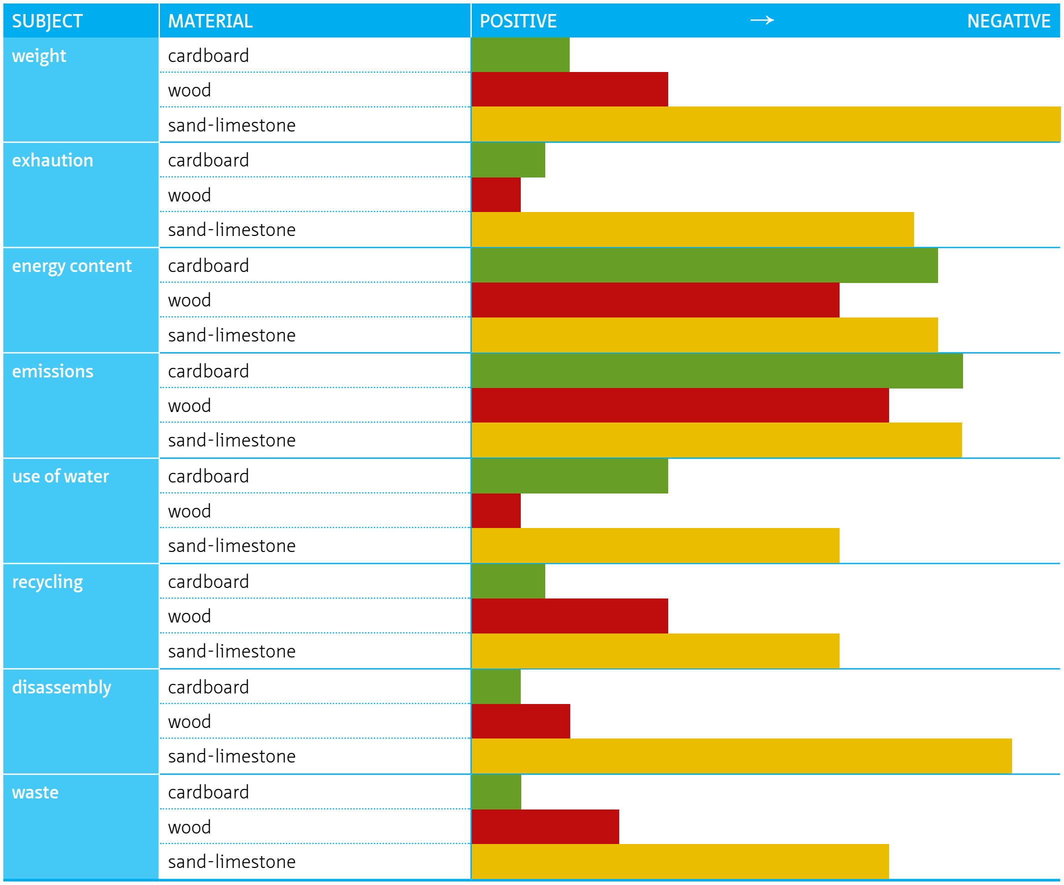

TABLE 3.1 Comparison of cardboard, wood and sand limestone in partitions per m²

The author of this thesis conducted further research comparing different types of partition walls as part of his doctoral research. The most popular type of partitioning in Poland was compared with a potential new product on the building market: cardboard panel walls. The wall was designed as a pre-fabricated partition wall consisting of several layers of honeycomb panels installed into a cardboard structural frame. Basic features such as assembly time, thickness, weight and price were compared (see Tab. 3.2). The values were then calculated for one square metre's worth of wall without any finishing layers.

WALL TYPE / FEATURE	CARDBOARD PANEL WALL	BRICK WALL (FULL CERAMIC BRICKS)	POROUS CONCRETE BLOCKS WITH LIME-CEMENT MORTAR (800) 150MM	SILKA CS BLOCKS	PLASTERBOARD WALL	GLASS BRICK WALL
Thickness	150mm	150mm	150mm	120mm	150mm	80mm
Weight	12-20 kg	220 kg	85-130 kg	195-225 kg	50-90 kg	70-90 kg
Acoustic insulation (Rw)	45 dB	46 dB	36 dB	50-56 dB	55 dB	38-45 dB
U-value (m^2K/W)	0.8 – 0.5	5.13	2.53	2.13	0.60-0.35	2.34-2.97
Fire resistance (minutes)	30	120	120	180	30-120	30-60
Connection type	Screws	Mortar	mortar	mortar	screws	Reinforcement, mortar or glue
Price* per m^2 (including work-load, exclusive of finishing)	PLN 90-120 (€21-28)	120-150 PLN (€28-35)	120-140 PLN (€28-33)	120-130 PLN (€28-30)	90-200 PLN (€21-47)	250-400 PLN (€58-93)

TABLE 3.2 Comparison of the cardboard panel wall with other traditional types of partitioning, per m^2

It can be observed that partitions made out of cardboard are lighter, cheaper and more quickly assembled. However, their acoustic insulation and fire resistance levels are lower. The price of traditional partitions were checked at the Polish building market in April 2017 by local research. The properties and price of cardboard partition walls were estimated based on available data (price per element, computer simulation for U-value, references to similar products with regard to acoustic insulation and fire resistance).

§ 3.3.6 Art and performance

Paper and cardboard are also used for artistic activities and performances. Founded in Russia in 2007, Cardboardia – a cardboard utopia, where the ideas and dreams of its creators are being realised by means of cardboard – is a socio-political manifesto as well as a cultural and artistic project, whose members have a *child's freedom* to express their needs, dreams and convictions. [24] Once a year, during the Cardboardia *materialisation* event, the imaginary state of Cardboardia with its cardboard cities is created (see Figs. 3.37 and 3.38). All residents, citizens and tourists can participate in Cardboardian society. Every year the state is built from scratch. The cardboard utopia is a place where, according to the idea stated by its creator, Sergiej Korsakov, personal expression is celebrated. It is a project that connects international societies and allows their members to bring to life their ideas and artistic visions by using cheap and available material. The most active members of Cardboardia come from Russia, the USA, England and the Netherlands. The current population of Cardboard consists of tens of thousands of people. Cardboardia is also the biggest exporter of decorations, arts and crafts and furniture made out of cardboard, which can be purchased from its website. In July 2015, the Cardbordia event took place in Lublin, Poland. [6,11]

FIGURE 3.37 Mobile Embassy of Cardboardia in the city of Lublin, Poland, 2015

FIGURE 3.38 Cardboardia in the city of Lublin, Poland, 2015

§ 3.3.7 Production costs and market prices

One of the great advantages of cardboard as a material is its low cost of production, despite the high prices of some of the furniture created with it. Because its designer is a famous architect, and also because it is a high-quality product, Frank Gehry's Wiggle Chair costs €750, although the costs of the material do not exceed €20. Shigeru Ban's Lounge costs a whopping €900. On the other hand, Chairigami's Lounge Chair costs €95 and the Paperpedic bed produced by Karton Group costs €165 for a basic version and €450 for the whole bedroom furniture set.

The Paper Miracle proposed by the Humanisation of the Urban Environment group – a space for creative meetings in the office – costs €135 for a set dividing a room measuring 4x4m, with a height of 2.25m.

One package of Nomad System Room Dividers, which allow one to assemble a partition measuring 2.74mx0.9m, costs €53.5. The cheapest partition produced by BIA Systeemwanden, which consists of a gypsum liner and a corrugated cardboard core, costs €19.39 per square metre. The more exclusive softwall product costs €880 per segment. The aforementioned prices are correct of as year-end 2016.

The fact that some of the products are so expensive despite the fact that their materials and production are so cheap can be attributed to different marketing strategies and different target groups. While the products designed by Gehry and Ban are geared towards wealthy individuals, the products designed by Chairigami and Karton Group suit almost any budget. The Foldschool project is an open-source pattern that can be downloaded and used free of charge.

§ 3.4 Exhibition pavilions, stage sets, structures for temporary events

This category encompasses structures built for special occasions like exhibitions, trade fairs, festivals, major sporting events and other temporary events. Many structures built for such purposes only last a few weeks or months. After demolition they generate a lot of waste, especially when they are built out of traditional materials, such as concrete, steel or wood. Cardboard and paper-based materials can be used to construct the venues for such occasions, and after being used, such structures can be dismantled and the material can be recycled or utilised, resulting in a smaller burden on the environment than would be the case if traditional materials had been used. Sometimes these structures seem to be abandoned after the event. Naturally, not all structures can be built out of cardboard, but in some cases the use of recyclable materials can result in positive outcomes.

A good example of such a situation is the city of Sochi in southwest Russia, which hosted the 2014 Winter Olympics – the most expensive Olympic Games in history, which cost the Russian Federation about $50 billion. One year after the Olympics, this city with a population of 300,000 and with an incredible number of new and unfinished buildings, looked like a ghost town. [25, 26] The question will always remain how to manage places that were used intensively for a short period of time. It seems host cities often lack a strategy for the future. An example of the opposite is the Olympic Park in London, where after the 2012 Summer Olympics, the venues built in east London (historically the poorest part of the city) resulted in new public spaces for cultural and sporting events and for everyday activities. The discussion about the sense of spending £9.3 billion on a temporary event like that is still ongoing. For instance, the former mayor of London, Ken Livingstone, characterised the investment as 'the only way to get billions of pounds out of the government to develop the East End'. [27] The case of London is a good example to follow, on the condition that such a venue is built next or within a big city or agglomeration and can serve later as a place for leisure and culture, filled with housing estates. However, many venues, not only for the Olympics but for all sorts of events, bring degradation and waste, unless they are designed and built in a way that allows the materials to be re-used or recycled. Such problems can be solved by using degradable materials, which can be recycled after the lifespan of the structures with minimal impact on the cultural landscape and the environment. An example of such a structure would have to be the Pappedern, i.e., small utility units, made out of cardboard, designed by 3h design for the 1972 Munich Olympics (see also Section 4.1: The history of paper in architecture).

The size of the structures included in this category can vary from Medium to Extra-Large, while their lifespan is several weeks or months; it rarely exceeds one year.

In general, the structures included in this category can be divided into two types: indoor and outdoor.

§ 3.4.1 Indoor pavilions, exhibitions, stage sets

Indoor pavilions are created from different paper-based materials, but mainly from corrugated cardboard, honeycomb panels and paper tubes. They are realised to serve as venues for different types of activities, e.g. fairs or exhibitions. Alternatively, they can be works of art.

In 2001 architect Daniel Libeskind was awarded the Hiroshima Peace Prize for his projects that promote international understanding and peace. Following the award ceremony, an exhibition entitled 'Four Utopias of the Six Stages of Existence' of the architect's works was opened in the Hiroshima Museum of Modern Art in July 2002. The exhibition presented four projects in the form of 1:5 scale models of the buildings and the author's drawings: the Felix Nussbaum House in Osnabrück, the Jewish Museum in Berlin, the Imperial War Museum North in Manchester, and the plans for his extension to the Denver Art Museum. Since the exhibition would later be moved to the ICC Museum in Tokyo, it was decided to create the exhibition in the form of a travelling show. In order to construct four mock-ups of the buildings, which were approximately 30m in plan and up to 10m high, 20mm honeycomb panels were used.

The honeycomb panels were connected to each other by means of cardboard angles glued and screwed to the honeycomb panels (see Fig. 3.39). [23, 28]

An example of an indoor art structure made of cardboard was the Rip Curl Canyon, an installation designed by Benjamin Ball and Gatson Nogues in 2006 for the Rice Gallery in Houston, USA. The installation consisted of 20,000 individually prepared components made of corrugated cardboard laminated into a wooden framework. It weighed approximately eight tonnes. The designers, who were inspired by Frank Gehry's Easy Edges furniture, expanded the knowledge of the material by means of parametric digital interface and by making full-scale mock-ups. Later they used industrially die-cut stripes of cardboard, which were then laminated together, and with the help of plywood armatures formed the three-dimensional shape of a cardboard canyon (see Fig. 3.40). The composition was a reference to the mythical Rip Curl Canyon, located in the western USA, where land and water collide. The structure, whose sizes were calculated in association with ARUP Los Angeles, was strong enough to support visitors climbing, snoozing and sliding down the installation. The Rip Curl Canyon was not the only cardboard art installation designed by the Ball-Nogues Studio. In the same year they also designed the Tiffany & Company Gehry Jewelry Launch, to mark the occasion on which Tiffany & Company launched Frank O. Gehry's jewellery line. This temporary structure was composed of 4,000 pieces of corrugated cardboard laminated together to form a human body, with display windows. The corrugated cardboard external wall was supported by 24 ottomans, also with organic shapes. Yet another project of the Ball-Nogues Studio was the Sculptural Cardboard Workspace, which fits into the furniture category. [6, 29]

FIGURE 3.39 Model of Denver Museum, Libeskind Studio, 2001

FIGURE 3.40 Rip Curl Canyon, Ball-Nogues Studio, 2006

In 2008 Shigeru Ban designed a Paper Tea House for Phillips de Pury & Company, an auction house in London. The structure, whose dimensions were 2x5.38x2.6m, consisted of square paper tubes laminated together to form the components of a house. The wall components were connected to each other by steel rods, and the roof was made of folded paper. The floor and the furniture were also made of square paper tube, except for the table, which was made of honeycomb panels (see Fig. 3.41 and 3.42). As mentioned in the auctioneer's catalogue, the house was an *ephemeral building, a shelter for poetic feelings. It is also the "House of Emptiness," for it is free of all ornament, except for what little is necessary to satisfy the aesthetic aspiration of the moment. Finally, it is the "House of Asymmetry" in that it is destined for the cult of the incomplete, and some small detail is always left unfinished, so that it may be completed by the play of the imagination*. The estimated cost of the house was £40,000-60,000. [30, 31]

FIGURE 3.41 Paper Tea House, Shigeru Ban, 2013

FIGURE 3.42 Interior of the Paper Tea House, Shigeru Ban, 2013

In 2010, a team from Wroclaw University of Science and Technology's Humanisation of the Urban Environment scientific organisation designed and built a pavilion to mark the occasion of the 100th anniversary of the technical universities in the city of Wroclaw and the 65th anniversary of WUST. The pavilion, called 'Memory Mailbox', was designed and built by Michal Antos, Kamil Bocian, Jerzy Latka, Malgorzata Los and Anna Weber. The pavilion consisted of corrugated cardboard boxes and was shaped like a 5m long tunnel in which selected boxes were used as postboxes for alumni from different years of WUST's 65-year history (see Figs. 3.43, 3.44). Visiting alumni could use specially prepared stationery and write down their personal memories of their student days. The boxes were connected to each other without any additional material or glue, by inserting the flaps of folded boxes into the spaces between the flaps of adjacent boxes. Only at the bottom part of the ceiling of the pavilion staples were used to keep together the boxes next to it. The bottom boxes, which served as the foundation, were filled with weights. The pavilion was exhibited at one of the university buildings for about two weeks.

FIGURE 3.43 Memory Mailbox, Humanisation of the Urban Environment group, 2010

FIGURE 3.44 Memory Mailbox, Humanisation of the Urban Environment group – view from above, 2010

The Swiss artist and musician Zimoun creates 'architecturally-minded platforms of sound'. [32] In his art installations, cardboard boxes are used as both a dividing wall and the membranes of drums. By means of electrical engines and balls made of cotton or cork and attached to the engines, Zimoun creates spaces filled with rhythmic constructions that surround the audience (see Figs. 3.45-3.47). The balls driven by the engines rhythmically patter the boxes, but at different intervals. All the cardboard boxes are the same size, and all the engines are the same, as well, but the wires connecting the balls with the engines have different lengths and are attached at slightly different angles, which results in them each having their own rhythm. The internationally appreciated artist creates compositions that are reminiscent of natural constellations without imitating nature.

FIGURE 3.45 Zimoun's installation at Dutch Design Week, Eindhoven, 2014

FIGURE 3.46 Interior of Zimoun's installation, Eindhoven, 2014

FIGURE 3.47 Close on Zimoun's installation, Eindhoven, 2014

Founded in 2012, Austrian company Papertown realises stages, pavilions, trade stand, fair booths, furniture and art installations made out of cardboard (see Figs. 3.46 and 3.47). The company's portfolio contains over one hundred cardboard products and structures to be used indoors. The projects are designed, transported, installed and maintained by the company itself.

Cardboard was a material of choice for the designers for several reasons: the material is light and easily shaped, which means that the finished objects can be easily changed if necessary. It is also cheap and will most probably remain cheap due to the increasing amount of recycled paper and cardboard. The production process is easy, especially when using machine-driven manufacturing methods. After preparation, elements can be easily transported and stored in the form of unfolded flat boards. The material can be painted and printed, and ongoing research conducted by the industry and scientific units is improving its qualities. Last but not least, cardboard is a sustainable material. The Papertown team mainly uses corrugated cardboard in its projects. Cardboard amounts to at least 90% of the materials used in the products, which makes the products eco-friendly. Eighty-five percent of the cardboard used is recycled and can be further processed after use. [33] Philipp Blume, the founder and CEO of Papertown, was honoured with an iF Design Award in the Interior Architecture/Exhibition Space Design category in 2016.

FIGURE 3.48 Cardboard Art House, Papertown, 2016

FIGURE 3.49 Konica Booth, Papertown, 2016

A group of TU Delft students under the supervision of Friso Gouwetor, Mark van Erk and the author of this thesis designed and built the Tree D Papervilion (see Fig. 3.50). The pavilion was the result of a Design Informatics course taught as part of the Building Technology curriculum at the Faculty of Architecture. Twenty-one students (Tim Neeskens, Eline de Vries, Marit de Groot, Rosanne Berkhout, Ákos Szabó, Bahareh Miri, Veerle van Es, Finn Dahlke, Dora Vancso, Jerry Pollux, Pim Buskermolen, Alex Kouwenhoven, Michael Cobb, Nikki Fung, Paul Johan van Berkel, Anne de Schepper, Tarik Alboustani, Alvaro Rodriguez Garcia, Congrui Zha, Antigoni Karaiskou and Lia Tramontini) divided into smaller sub-groups designed and developed the free form interactive info pavilion.

The Tree D Papervilion consisted of two elements. One was a paper tree, which was made out of paper tubes, connected to each other by means of 3D-printed joints. The joints were made out of translucent PLA (polylactide), which allowed the students to light the joints with LEDs from the inside. The wiring was connected to controllers that allowed users to change the intensity of the light. The second element was a bench made of honeycomb panels that was connected with a doubly-curved screen. The screen was made out of honeycomb panels 5cm thick. The panels were first stripped of their outer layers of paper, then placed onto a special mould, which enabled the creation of the double curvature. The new top and bottom layers of the paper were then laminated. The doubly-curved panels were connected to each other by means of specially designed flexible joints, made out of laser-cut plywood (see Fig.3.51). The Tree D Papervilion was built in Alicante, in association with Alicante University. A group of designers and students from Alicante University and York University in Canada then copied the Tree structure and further developed the lighting and robotic movement of the branches. In the end, both structures (one in Elche, Spain, and another in Toronto, Canada) were exhibited on 7 July 2017.

FIGURE 3.50 The Tree D Papervilion

FIGURE 3.51 The Tree D Papervilion, flexible connection between double-curved plates, 2017

In 2017 Marcel Bilow, Dina Cheliadina, Karolina Dyjach, Olga Gumienna, Ewa Hejducka and Jerzy Latka created a pavilion called the Paper Cave. The Paper Cave was a project designed for the exhibition pavilion for the 2017 European Paper Week. The Pavilion was 590cm long, 220cm wide and 250cm high. The Paper Cave consisted of 118 layered cardboard honeycomb panels (5cm thick) laminated into prefabricated components (see Fig. 3.52). The components' size allows them to be transported

(120x250x90cm). The components were easily put together, by screwing the bracing board to the wooden battens hidden in the structure.

The Paper Cave was designed in order to showcase a different and contradictory perception of paper. From the outside the pavilion had straight walls, in which layers of honeycomb panels alternated with translucent Plexiglas stripes illuminated with cold blue LED light. This exterior showed off the ordered structure of paper in the form of stacked cardboard sheets, while at the same time showing its plasticity. The Plexiglas stripes dimmed the light emitted by the LEDs that were installed in between the layers of honeycomb panels.

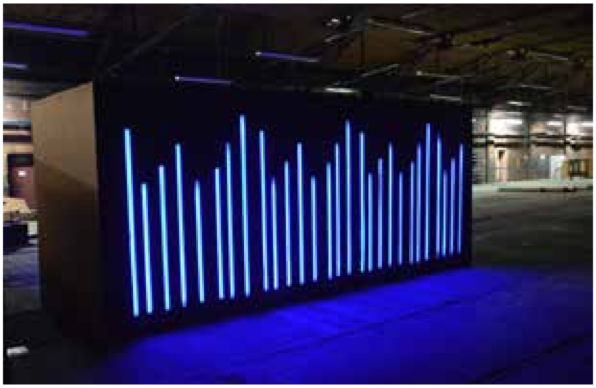

FIGURE 3.52 Paper Cave exhibition pavilion, archi-tektura.eu, 2017

FIGURE 3.53 Paper Cave interior lit by LED lights, 2017

The interior of the pavilion was an organic and chaotic space, even if it was made out of 10 repetitive elements. This interior of the structure was meant to remind visitors of the natural and organic origins of paper (see Fig. 3.53). Five special niches (width 70cm, depth 50cm and height 100cm) were incorporated into the interior, where five innovative paper products were displayed. The interior of the pavilion was illuminated by blue LED light. This cold light complemented and balanced out the warmth of the natural colour of the honeycomb panels. The tension thus created between the interior and exterior of the Paper Cave was a reference to the high technology involved in paper production and the low-tech and natural composition of paper.

§ 3.4.2 Outdoor pavilions

The main difference between indoor and outdoor installations made out of paper-based materials is the need to impregnate the latter against water and moisture. In addition, external climatic conditions like wind force have to be taken into account during the design process and calculations.

Students from the Department of Architecture at the University of Cambridge designed and built a Cardboard Banquette Pavilion in 2009. The pavilion was built to mark the start of a new term at the university. The structure was created by third-year students, who designed and built the pavilion. Its furniture was created by first-year students. The students were supervised by Tom Emerson, Ingrid Schröder, Max Beckenbauer and Rentaro Nishimura, a designer and specialist in architectural folding techniques. Fourteen students built the structure, which was based on a Yoshimura origami pattern and consisted entirely of corrugated cardboard. The folded plates were connected to each other by ropes. The pavilion was produced in three days and erected in several hours. It hosted eighty people during a party held on 23 October 2009 (see Figs. 3.54 and 3.55).

FIGURE 3.54 Cardboard Banquette Pavilion, Cambridge, 2009

FIGURE 3.55 interior of Cardboard Banquette Pavilion, Cambridge, 2009

Assistant professor Olivier Fritz, his assistant Tom Pawlofsky and students of the University of Liechtenstein built a 60m^2 Model-Making Pavilion in 2007. The pavilion was constructed from CNC-cut and machine-folded corrugated cardboard, covered with a PVC membrane. The curved pavilion was the result of computer-aided design and production research. Prof. Fritz and Tom Pawlofsky developed a new formwork system for free forms. This patented system is made of corrugated cardboard and can replace mass-produced, expensive and labour-intensive available solutions. [6, 34]

Tom Pawlofsky supervised a group of students from the Master Advanced Study group at the Department of Computer-Aided Architectural Design (CAAD) at ETH Zurich in Switzerland. Michele Leidi, Min-Chieh Chen and Dominik Zausinger, with the help of Jeannette Kuo, designed and prefabricated a cardboard pavilion called Packed, which was then shipped to Shanghai and built. Packed, which was part of the final exhibition of Shanghai Expo, was exhibited at the '3D Paper Art' exhibition at the Shanghai Museum of Arts and Crafts and at Shanghai's Fudan University in October and November 2010. The pavilion consisted of 409 truncated cones. Each of the cones was made of 28 layers of corrugated cardboard which were cut and laminated with a computer-controlled machine (see Figs. 3.56 and 3.57). The radius of the cones was calculated in such a way as to allow the cones to fit into one another to reduce the amount of material needed and to decrease the volume for transportation. The cones touched each other in one tangent point and were connected to each other by means of zip ties. The bottom cones had thicker walls but were smaller in diameter than the top ones to ensure the most heavily loaded part was stable, and also to allow more light to enter through the lighter cones at the top. The cones were covered with shrink foil to protect them against the weather. Production took place at ETH in Switzerland and the prefabricated elements were then sent to China. [35, 36]

FIGURE 3.56 Packed: cardboard pavilion, Shanghai, 2010

FIGURE 3.57 Corrugated cardboard cones

Public Farm 1 was a submission to the Young Architects' Program of courtyard installations organised by the PS1 Contemporary Art Center in New York. The New-York-based WORK Architecture Company designed the Urban Farm, which was created from paper tubes normally used as a formwork for underground concrete pillars (see Fig. 3.58). Public Farm 1 was built in the courtyard of the PS1 Gallery in 2008. The farm had two hills meeting at the lowest point. The paper tubes were organised in a daisy-shaped arrangement and were used as pots for 51 species of herbs, fruits and vegetables (see Fig.3.59). Six paper tubes were dedicated to one single species of plant, and the centre tube was used as a structural column or as picking station for harvesting the plants. Each of the structural columns had another function, as well, depending on the programme for the area. Some served as solar-powered juicers, periscopes or water-splashing columns, while others served as towel columns or solar phone-charging stations. Each paper tube had six wooden supports bolted to the cylinder from the inside, which provided structural stability and also held wooden discs. The discs were used as a base for the installation of the soil and plants. The paper tubes were impregnated, and the cut ends of the tubes were protected by steel rings. [6, 36]

FIGURE 3.58 Public Farm One, WORK AC, 2008

FIGURE 3.59 Public Farm One, view from above, WORK AC, 2008

In the words of its designers, the structure of Public Farm 1 was *Channeling the last utopian architectural projects about the City that examined its potential, represented its promises of liberation, and captured its pleasures — from Superstudio's Continuous Monument to Koolhaas's Exodus — Public Farm 1 (P.F.1) is an architectural and urban manifesto to engage play and reinvent our cities, and our world, once again*. [36]

The projects outlined in this section showcase the broad variety in temporary structures and compositions in which paper is used as a primary material. Regardless of whether the project was basic and small or rather a large pavilion or installation, cardboard and other paper-based materials were applied successfully. The projects realised indicate the high economical potential of using paper and cardboard in mass-produced elements for commercial applications. The fact that the material is recyclable and environment-friendly is one of the important factors in the market.

Other examples of cardboard structures for temporary use, such as the Japanese Pavilion for Expo 2000 in Hannover, the Apeldoorn Cardboard Theatre or the exhibition pavilion for Wroclaw University of Science and Technology realised by the author of this thesis are described in Chapter 4. The above examples were used to describe the range of possibilities and applications. The structures discussed in Chapter 4 will be categorised more specifically based on the structural system, connections between elements, impregnation methods and materials used, their connections with the ground, etc.

§ 3.5 Housing and buildings used by private clients

Contemporary architecture, or rather the contemporary world, is facing new and ever-changing challenges. Several of these challenges seem to be significant and will greatly affect future life conditions on earth.

The first issue is sustainable development, which may be understood as a physical development of a human environment, which should not cause harm to nature and our living environment, so that future generations will be able to use earth's resources as much as we do at present. But sustainable development means also an equal development of societies and their living conditions.

The condition of contemporary humans seems to be more and more unstable. People increasingly live in urbanised spaces. More than 54% of the world's population lives in cities [37]. Humans have become an element of a dynamically changing social and legal systems. The contemporary era, also called 'liquid modernity', was described by sociologist and philosopher Zygmunt Bauman as a modern time in which we are no longer connected to the places or concrete activities that were characteristic of the generations that preceded us. [38] Our traditional understanding of countries and nations has been replaced by international connections and social networks. Bauman shows that people are more connected to, say, international companies than to nation states. Humanity is in constant flux, and thanks to electronic media, where everyone can be a receiver as well as a provider of information, the traditional structure of society has changed completely. Humans have always believed in some perfect world with its own order. Several attempts have been made to create one – nearly always in vain.

Ever since Thomas More first described it, Utopia, being a better place to live in, has always been connected with an actual place. The name *Utopia* is derived from the Greek word topos, meaning *place*. In the sedentary stage of modernity, space and power were linked. Power was always related to a certain territory that was held by a powerful person or family. This territory was ruled, either by a royal family or by a government. As Bauman said (2003): *In the transgressive imagination of 'liquid modernity' the place (physical or social) has been replaced by sequences of new beginnings*. [39]

Local governments and nations are becoming less important. Authority is now held by international corporations, whose homeland is economy, and therefore money, and which are not attached to any one place. Young people nowadays are increasingly likely to travel a lot and to move from one place to the next in order to gain new experiences or to find a satisfactory job. [40]

People no longer plan their entire life. They only plan few years ahead. Our need for space changes, too, over the years. Our lives can be divided into chapter of up to twenty years: childhood, adolescence, young adulthood, adulthood and retirement. Each of these stages comes with different spatial needs. People use their homes for a relatively short time before moving on to a different home. Homes are tailored to their inhabitants' individual needs. After a period of residence, houses should be processed, reconstructed, used again in a new configuration or recycled.

Bauman's observations on fluid modernity are reflected by Eurostat statistics on migration. In the year 2010, 5.1 million people migrated in the European Union, which means that in this one year 5.1 million people either emigrated from or immigrated to an EU country. By the year 2013, this number had increased to 6.2 million and in 2014 the number rose to 6.6 million. [41, 42] The year 2015 presented new challenges in terms of migration. This time the influx of immigrants and refugees from the Middle East and Africa was caused by the Arab Spring, which started in 2011. The International Organization for Migration said that a million immigrants and refugees came to the European Union in 2015. Globally, the number of immigrants and refugees reached 244 million in 2015, which was 74 million more than in to 2007. [37]

Researchers have predicted that the level of migration in the EU will continue to grow, given the current plans for cooperation and the fact that Eastern European countries like Macedonia, Montenegro and Serbia, which currently have candidate status, will likely join the EU, Furthermore, the EU initiated a programme of intensified cooperation called the Eastern Partnership (EaP) in 2009. The Eastern Partnership consists of six former Soviet countries, namely Ukraine, Belarus, Moldova, Azerbaijan, Armenia and Georgia. [43] This will probably result in more migration to the EU. Moreover, the EU will have to import foreign labour in response to various social challenges, in view of its ageing population, low birth rates and the prospects of its social security system. [44] Furthermore, many immigrants are arriving from India and the Middle East. Most of these migrants are young twenty- or thirty-somethings.

As stated in Statistical Books of Eurostat:

Immigrants into EU Member States in 2013 were, on average, much younger than the population already resident in their country of destination. On 1 January 2014, the median age of the EU-28 population was 42 years. By contrast, the median age of immigrants to the EU-28 in 2013 was 28 years [41].

Economists and politicians have noted that today's young people are the first since World War II to start their independent lives in worse conditions than their parents. The lack of suitable housing and increasing unemployment in many European countries are resulting in frustration and confusion.

In this ever-changing reality, the humans less and less need a physical link to the territory or to the cultural codes that go with it. The *global village* lifestyle requires people to continually adapt to new, changing conditions and situations. Moving has never been so easy. Travel and a change of scenery, either because one needs a job or for training and education purposes, are becoming commonplace.

Therefore, it is reasonable to ask whether we still need houses built to last fifty to one hundred years, as previous generations did. The concept of a home has become more ephemeral. We hardly see multi-generational homes any more in which three generations of one family grew up.

The answer to the question asked above is a new generation of materials and structures. New solutions should involve sustainable, easily produced, low-cost materials with a limited lifespan which can be re-used, reset or recycled. Paper is such a sustainable, easily produced low-cost material with a limited lifespan.

Ozlem Ayan proved in her PhD dissertation that Swiss society, especially its younger citizens, would be willing to live in houses built to last ten to fifteen years if they were financially affordable and eco-friendly. [45] The project described in the work is called CATSE (Cardboard in Architectural Technology and Structural Engineering). Ayan and Pohl proposed a concept of Cardboard Housing in which a group conducted research together connecting architectural, social and structural approaches (described in a dissertation entitled *Strengthened Corrugated Paper Honeycomb for Application in Structural Elements* by Almut Pohl). [46]

Ayan describes in her dissertation the issue of high energy consumption in the Swiss building industry and increasing ecological awareness in society, which encouraged her to introduce a new sustainable and low-energy material to the market. Analyses of the lifecycle of cardboard, SWOT and PEST as well as a comprehensive questionnaire were used to position cardboard housing in the Swiss market. As Ayan noted in her dissertation, structural factors and a changing demography may affect the implementation of CATSE. In an ageing population, increased levels of immigration will decrease the median age of the population. CASTE is geared towards the lower age segment and may prove popular with first-time home buyers in Switzerland.

Ayan found that the three main themes that determined the adoption of CATSE in the building market were:

- **Cost**: the government can use its tax policy to give people an incentive to purchase eco-conscious homes.

- **Trends**: Swiss society is eco-conscious, it has introduced environmental construction standards. As Ayan mentioned: *By Minergie (*quality label for buildings that combines high comfort of living and low energy demand), *houses have an energy consumption which is 70% to 85% lower than the consumption of traditional houses built prior to 1970's or 50% lower of the standard of today's new buildings*. The CATSE houses are intended to stay on site for ten to fifteen years. Afterwards they will be reconstructed to meet new environmental and energy-efficient standards. Swiss houses that have the Minergie label tends to be 9% more expensive.
  According to Swiss Federal Office Statistics, more than two million of the country's seven million residents regularly move house. CASTE may make the move easier and may help people adjust their new homes so as to suit their changing spatial needs. As the family grows and grows smaller again.

- **Quality**:

  - Space
  - Easy access
  - Interior services and hygiene
  - Interior environment and health
  - Safety
  - Neighbourhood
  - Architectural expression
  - Technical aspects of construction

A survey of two hundred respondents measured Swiss people's level of acceptance of cardboard houses. Ayan stated two reasons that have brought attention:

- **Unconventionally short lifespan** (ten to fifteen years)
- **Cardboard as a building material**

The survey provided information on the following matters:

- **Relocation**: 80% of respondents moved house at least once in their lives; 1% moved house more than eight times; 30% moved house five to seven times; 40% moved house two to four times.

- **Consumer preferences** in new dwellings (independent categories and CATSE-related).

- **Negative experiences** with new dwellings.

- **Associations with cardboard as a building material**. Positive associations 17%: universal, modular, disposable, easy installation, good insulation, strong, stable, useful, creative, environmentally friendly, foldable, light, efficient, flexible. Negative associations 11%: flimsy, temporary, unstable, strange smell, glue, useless when wet, humidity, buckling, noise, weak, ugly, flammable, uncomfortable to the touch.

- **Associations with cardboard buildings**: 47% structural problems, 49% structural integrity under bad weather conditions, problems related to joints, sealing and friction, stability in strong winds, overall security, 50% water/humidity, 10% durability. Personal comments: there is a stigma attached to cardboard, as it is a material used by homeless people.

- **Increasing the acceptance rate of cardboard buildings**: 32% require further scientific test results and proof that cardboard is stable, waterproof, fireproof and secure; 22% would accept cardboard buildings if they had a chance to experience a finished product at an exhibition fair; 27% had heard positive stories about experiences with cardboard houses from colleagues and friends; 10% had come across positive reports in the media; 2% felt commercial advertisements would be an effective way to persuade them.
  In the Swiss building industry, one-third of investments in the private sector and 55% of investments in the public sector can be attributed to attempts to upgrade Switzerland's ageing buildings. Since these high rates of renewal/refurbishing play a prominent role in the amount of construction work being carried out, and since

reports confirm that people are moving house more often, a system that requires reconstruction every ten to fifteen years may prove to be regarded as an advantage. The CATSE model initially attracted interest from the government and private entities. The product needs to be trusted by the market.

With regard to the societal approach to cardboard housing Ayan concluded that development strategy for CATSE should follow three lines:

– Positioning of CATSE – Swiss people are highly conscious of the quality of their housing and are becoming increasingly environmentally conscious. Corrugated cardboard will satisfy the ecological and economic demands of cardboard housing. The short lifecycle of cardboard houses will not necessarily put users off, because the rate of refurbishment, renovation and removal in the Swiss building market is relatively high at present. In addition, renovation and refurbishment are quite expensive, meaning that people may welcome the opportunity to discard their houses after few years and move into a cheap new homes.

– Positioning of the Swiss construction industry, which is currently experiencing a boom.

– The trend of innovative environmentally friendly housing and its impact on cardboard housing.

Ayan and Pohl proposed a certain solution for a cardboard house, which was a corrugated honeycomb wall panel used both as a construction wall and as a partition wall. The proposal for the cardboard house involved various types constructed on the same spatial scheme. Unfortunately, the cardboard house was not built, so the research and thesis remain as a theoretical approach.

Actually realised examples of cardboard houses are presented in Chapter 4. They include projects like Shigeru Ban's Paper House (see Section 4.3.3) and the mass-produceable Wikkel House, which represents the private market of residential buildings (see Section 4.3.15).

§ 3.5.1 Paper houses for the elderly - unbilt

The author's own proposal for a paper house was a design prepared in cooperation with Prof. Zbigniew Bac from Wroclaw University of Science and Technology. The conceptual project involving experimental houses for elderly people is scheduled to be built in near Zielona Gora city in Poland.

The project is an experimental housing estate which will consist of nine segments. Each individual segment will consist of two small ground-floor apartments (see Fig. 3.60). The segments will be able to be built independently in a multi-phase realisation process. The apartments, which measure 46m², will be located on either side of a pathway on a north-south axis. This arrangement will allow light to enter the houses from the south west and south east during the day. Bedrooms will receive light from the east or west, depending on the segment.

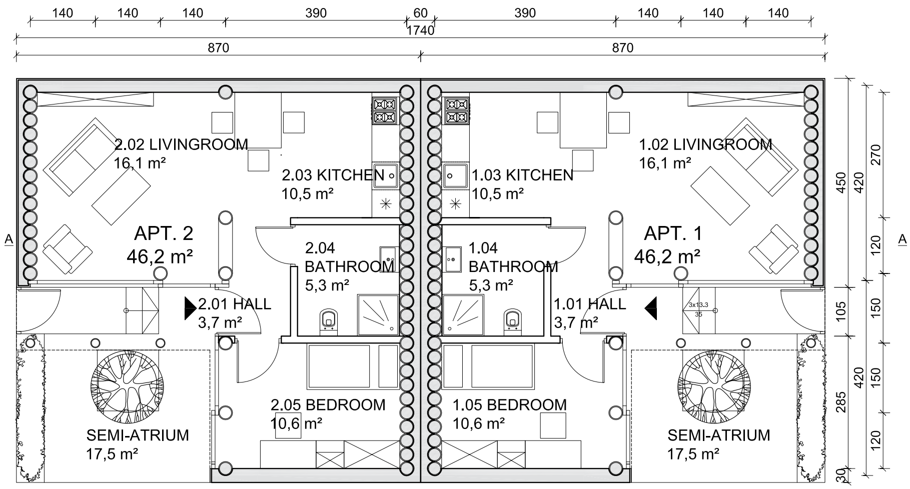

FIGURE 3.60 Houses for elderly people: cardboard segment, floor plan, 2012

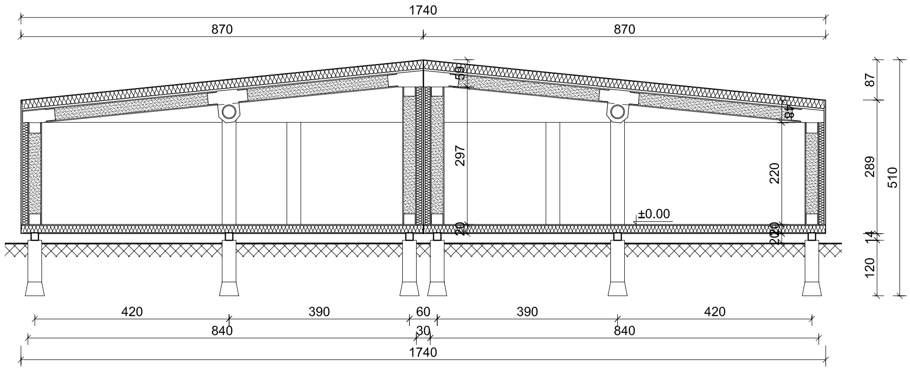

FIGURE 3.61 Houses for elderly people: cardboard segment, section A-A, 2012

Each apartment consists of:

- Entrance hall 3.7m^2
- Living room 16.1m^2
- Kitchen with dining room 10.5m^2
- Bathroom 5.3m^2
- Bedroom 10.6m^2

Furthermore, each apartment has an semi-atrium of 17.5m^2.

The rooms are lit by light entering through the semi-atrium, which also serves as a small garden and entrance area. The atrium can be reached from both the living room and the bedroom.

The building was designed as an experimental structure made out of cardboard components. Structural walls on the sides and in the middle of the building transfer the load from the roof. They were designed as rows of columns made of paper tubes whose diameter was 300mm and whose walls were 20mm thick. In order to improve their thermal insulation properties they were filled up with Styrofoam granulate.
The paper tube walls were covered from the outside by an insulating layer made of the cellulose fibres (Warmcel Excel), and lightweight HPL (High Pressure Laminate) elevation panels or a mixture of straw and clay. The partition walls were designed as lightweight cardboard panels, framed and filled with acoustic insulation material. The paper tubes were connected to each other by wooden joints fastened by screws and bolts. In accordance with the 'light-touch-of-the-ground' idea, the foundations of the entire segment were made out of fourteen reinforced concrete pillars with dimensions of 30x30cm and a height of 100cm. The roof structure consisted of rows of paper tubes

connected to each other by means of spongy tape. The tubes were connected with the walls by means of wooden joints which were slid into the roof and wall tubes. The roof structure was supported in the middle by the horizontal paper tube beams lying on the load-bearing inner walls (see Fig.3.61). The paper tubes that formed the roof were covered from above with thermal insulation material and a metal finishing layer. The external walls, which did not transfer any loads, consisted of honeycomb panels covered from the outside with HPL panels or attached to the adjacent building.

The experimental paper house for an elderly person is part of a bigger project led by Prof. Zbigniew Bac, in association with the University of Zielona Gora and the Arka Foundation. Nine segments are scheduled to be constructed. Each of these segments will consist of two apartments based on the same layout. According to Prof. Bac, the idea is that each segment will be built using a different technology and different materials (bales of straw, wood, bricks, clay, etc.). [47]

§ 3.6 3.6. Public buildings

Public buildings which have been made of paper-based elements so far include schools, university buildings, sport clubs, galleries, meeting spaces, etc. These structures are built to last for twenty years. However, there are several examples of paper buildings that have been recognised as permanent structures, such as the Nemunoki Children's Art Museum by Shigeru Ban (see Section 4.3.6) or the Ring Pass Field Hockey Club by Nils Eekhout (see Section 4.3.12). On the other hand, there have also been some public buildings made out of paper with a lifespan of just a few weeks or months. The most common reason to use paper as a building material in public buildings is the desire to overcome structural or architectural boundaries by architects and engineers and the promising environment-friendliness of the material. However, the ecological issue is in many cases not yet improved and elaborated. A good example of such ecological motivations is a building owned by the Westborough Primary School, designed by Cottrell & Vermeulen Architecture and BuroHappold Engineering (see Section 4.3.8). The structure of the building is made out of cardboard and wood, but the foundations are concrete, and their weight makes up approximately 80% of the weight of the entire building. One would think that buildings made of paper, a material that can be cheaply mass-produced, would not cost very much. However, this is not the case with public buildings. As they are built only once and generally are spectacular in terms of structural or architectural solutions, tests and experiments have to be conducted for almost every building. Therefore, it is common for revolutionary and innovative designs to be at least twice as expensive as traditional solutions.

§ 3.6.1 Bije(e)nkorf – unbuilt

Authors: Jerzy Latka, Julia Schonwalder
Year: 2017
Location: Dakpark, Rotterdam, the Netherlands
Area: 65.4m² (size: L)
Lifespan: Permanent (twenty-year lifespan)
Type: Public building

Bije(e)nkorf is the author's own proposition for a public building made out of prefabricated cardboard elements. Designed together with the engineer Julia Schonwalder, Bije(e)nkorf was a submission in an architectural contest for the social and meeting spot in Rotterdam's Dakpark. [48] The main structural elements were paper tubes and sandwich walls made out of honeycomb cardboard panels. The design also involved 10-feet shipping containers and a grid of timber pillars and laminated timber rafters.

FIGURE 3.62 Bije(e)nkorf, visualisation, 2017

Bije(e)nkorf is an innovative and pro-ecological solution for an innovative place: Dakpark, Rotterdam. Bije(e)nkorf is a place where the local community can get together, work together and relax. The form of the pavilion reflects the waves of water, which is vital to the port city that is Rotterdam (see Figs. 3.62 and 3.66). The organic form of the pavilion fits into the context of the city's green roof. The pavilion is divided into several zones. There are two zones for outdoor activities; both the south and the north sides of the pavilion are covered by a canopy roof. The interior is divided into several functional units (see Fig. 3.63). A kiosk is located inside the building, next to the entrance. Next to that, the main sliding doors lead the way to the entrance to the pavilion. The door can be left open, so that the interior and exterior of the building can become one. The ground floor boasts an open-concept common room and kitchen with a floor area of 30m^2. The space can be adjusted depending on the user's needs and activities. There is also a separate area measuring 4m^2 for individual work (a flexible work spot). Behind the kitchen is a service room with storage space. All the pro-ecological installations are located in the service room. They include storage for grey water, photovoltaic batteries, etc. Furthermore, there is a composting toilet that can be accessed from the outside and a small storage shed for garden tools. On the second floor there is a meeting room, which simultaneously serves as a place where plants can be cultivated. On warm days, the glass panels of the meeting room can be opened, thus transforming the room into an open terrace located on the south side of the building. The second floor can be accessed by a staircase that is easy-going for both young and old people. An additional storage space can be found under the stairs.

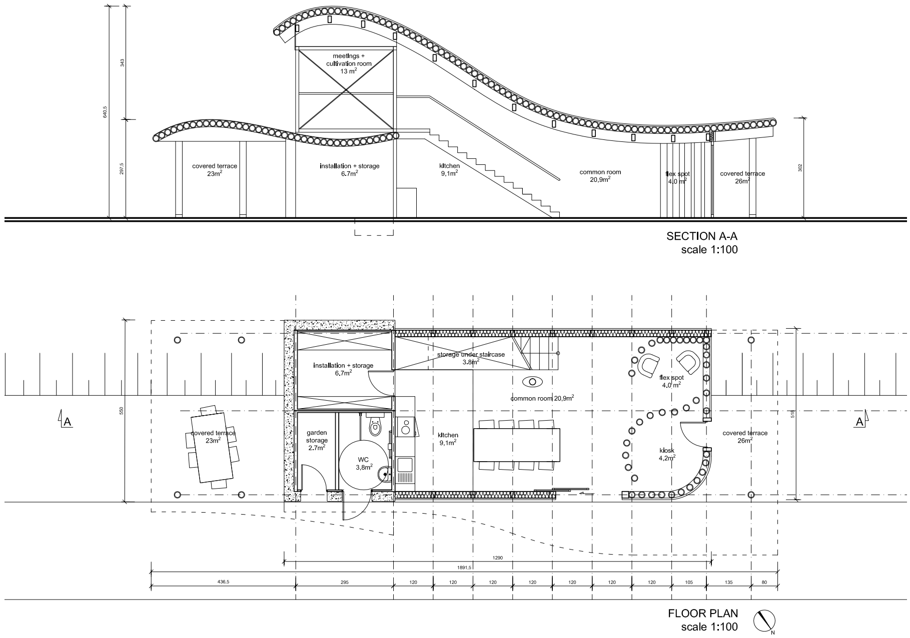

FIGURE 3.63 Bije(e)nkorf, section and floor plan, 2017

The Bije(e)nkorf was designed to serve as an innovative and eco-friendly pavilion (see Fig. 3.64). The structure of the southern part, which has two floors, is made out of four ten-foot shipping containers. One of them is already in use on the site and can be incorporated into the building. The walls of the ground floor of this part of the building are clad with bales of straw bales and clay. An *insect hotel* is installed in these organic walls. The upper part of the building is glazed and can be opened on warm days, on which it will serve as a south-facing terrace. Another part of the pavilion has a mixed timber-and-cardboard structure. Timber pillars and beams carry the roof, which consists of paper tubes impregnated against moisture and fire and also covered with PVC membrane. Water from the roof is collected at the back of the building and re-used as grey water in the kitchen and in the toilet. The wall panels with round windows are composed of paper honeycomb panels with high thermal insulation properties. The interior partitions are partly made of paper tubes, which determined the exact size of the kiosk and the flexible work spot. The material can be obtained from recycling and can be recycled afterwards.The estimated budget of the 65.4m² building was €100,000.

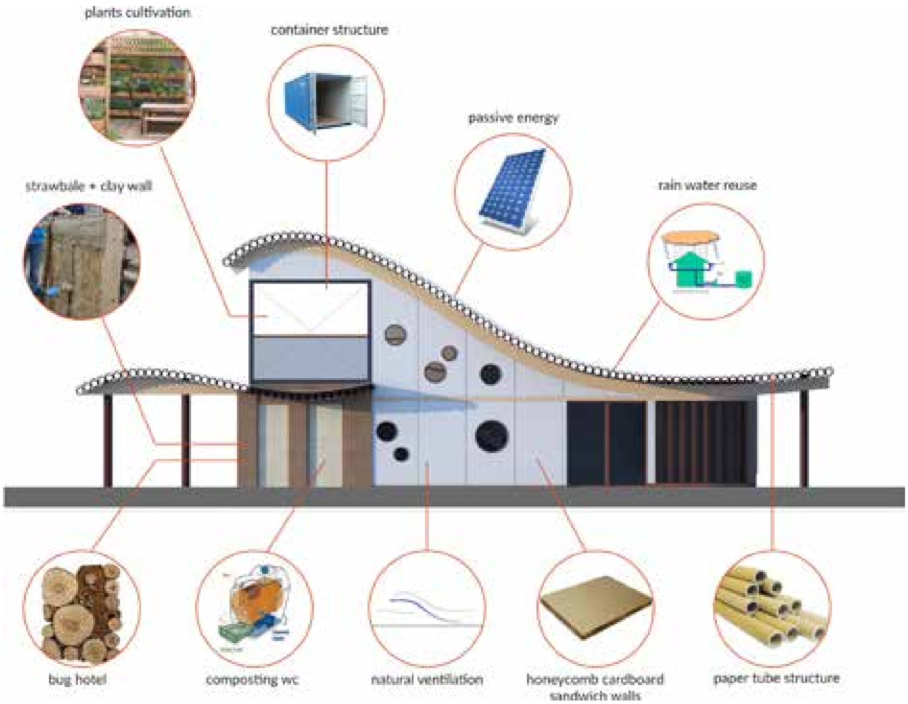

FIGURE 3.64 Bije(e)nkorf, section and floor plan, 2017

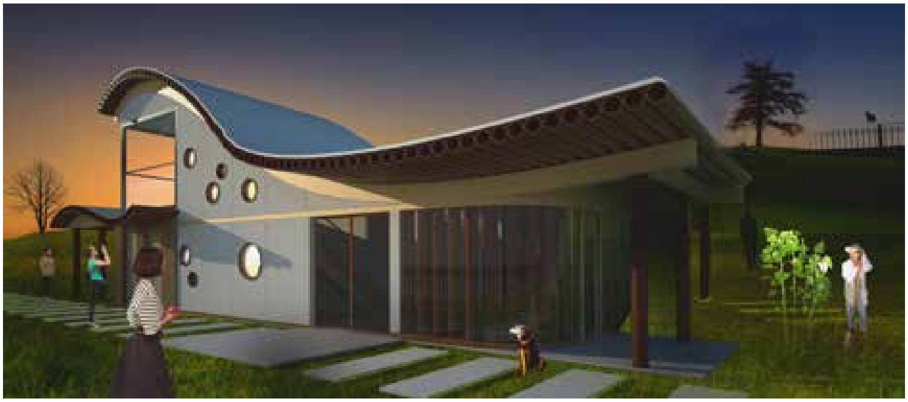

FIGURE 3.65 Bije(e)nkorf, visualisation, 2017

Selected public buildings made out of paper and actually realised are described in detail in Chapter 4: Paper structures. Case Studies.

§ 3.7 Emergency buildings

Emergency and relief buildings, intended for people who have lost their houses due to poverty, social exclusion, natural disasters or human-made disasters, are described in section 5.5 of the Chapters 5.

§ 3.8 Conclusions

Several aspects have to be taken into account when one uses a paper-based material The previously presented projects show that paper base materials can be successfully used for production of different types of design products and architectural structures.

There are five main functional categories, where paper is implemented as a main building material. Those are:

- Furniture, interior design, industrial design, arts and crafts and products for everyday use.
- Exhibition pavilions, scenography, objects for temporary events.
- Houses and building used by private customers.
- Public buildings.
- Emergency and relief architecture.

Those categories can be realized in four different scales (S, M, L and XL) which not only reflects to the physical size of the objects but also the complexity of the structure, the budged and expenses as well as the process of design, research and implementation.

Several aspects have to be taken into account when one uses a paper-based material for the production of interior and industrial design, arts and crafts, products for everyday use or temporary structures such as pavilions or exhibitions. These include the production process and processing of the material, as well as the need for harmonisation between cardboard and paper producers and designers, end product manufacturers and marketers, especially when series or mass production of the products is expected. Paper and cardboard definitely have pro-ecological connotations, especially when recycled material is used and the product can be recycled once more after its lifespan. For this reason, the popularity of paper and cardboard in furniture and interior design has increased since the late twentieth century. The most suitable types of paper for use in furniture and interior design are Kraft packaging paper, paper tubes, corrugated cardboard, honeycomb panels and paper board. Another excellent option is Japanese washi paper. However, the latter is hand-made, therefore expensive. Paper-based materials' low resistance to moisture should be taken into consideration during the design and production processes. However, products to be used indoors are obviously less likely to be exposed to moisture. Another aspect that should be taken into consideration is the flammability and public perception of the material.

An important factor that affects the quality and price of a product is whether or not the design is valuable, as will often be the case with products created by famous designers. When this is not the case, the price of a product will only be a few times higher than the costs of the material and production. Furthermore, the product will be even cheaper if recycled material is used. In many cases paper and cardboard products are designed to be folded and assembled by the customer, and are distributed in flat packs. The characteristic factor of partitioning projects involving paper-based materials is their modularity and flexibility.

The products presented above, from the small-sized furniture, interior design, industrial design, arts and crafts and products for everyday use category are just a small part of the vast array of objects and buildings made of paper and cardboard. Bigger structures like pavilions, houses, public buildings and emergency architecture pose a completely different challenge in terms of research, design, production and implementation. The broad variety of implemented temporary structures presented in this chapter, prove that cardboard and other paper-based materials are suitable for small and large pavilions and installations. The presented projects indicate the high potential of using paper in mass-produced elements in commercial applications.

Looking at the dynamic of contemporary human and constant changes in spatial needs of one's house it is reasonable to ask whether the houses built for fifty to one hundred years are needed in the same extend as before. The concept of the a home has become more ephemeral. Therefore a new generation of materials and structures which are sustainable, easily produced, low-cost and can be re-used or re-cycled after the life-span of the building become a new market demands. Paper and its derivatives can fulfil this demands and become a complementary material to the traditional building materials existing on the market.

On the other hand buildings made out of paper-based elements require a vast research and development, which often results in high costs of the construction and time-consuming preparation works. Nevertheless the innovative approach and breakthroughs in science, design and architecture, even if requires large investments and extended research are the only way to achieve a development of the societies.

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4 Paper structures. Case studies

Good design can create strength from weakness

'Shigeru Ban: Paper in architecture' [1]

The examples of paper architecture presented in this chapter show the wide variety of materials and compositions used. The chosen examples are divided into two sections. The first section, entitled ‘The History of Paper in Architecture,’ embraces the projects realised from the late nineteenth century to the late 1980s. The examples provided in the ‘Case Studies’ section were assessed more thoroughly for their function, structural system, usable area, used material, connections and details of the structure (foundation, walls, roof), impregnation and lifespan. The chosen projects represent the most interesting solutions as far as structure and use of materials are concerned. Each of the examples described in this section presented an element of novelty in the world of paper architecture.

§ 4.1 The History of Paper in Architecture

The tradition of using paper in architecture dates back to ancient China and Japan. The earliest example of paper partitions in the form of folding screens produced in China date back to the eighth century AD. Although China is the country where paper was first invented, the Japanese later further developed paper-making techniques and made paper a common ingredient in architecture in the form of shoji (translucent paper screens), fusuma (sliding paper panels) and other parts of buildings (see Fig. 4.1.) [2]. It is said that most Japanese houses are made out of wood and paper. In the traditional way of life, paper was used for many applications around the house. As described by Mitsuhiro Ban in the Handbook on the Art of Washi: ‘Differing from such non-organic material as concrete, steel and glass or such non-organic and hard material as synthetic resin, paper and wood once were living. Therefore, they respond to our inner psychology and speak to us with strong and silent words’. [3]

Since paper was invented and disseminated by Cai Lun, a Chinese minister for agriculture in the Han dynasty, in the second century AD, the main idea behind paper-making has not changed much. [4] Despite the fact that the machinery has changed over the years and paper-making was industrialised in 1799 with the invention of the first model of the continuous paper machine by Frenchman Louis Robert, [4, 5] paper is still a layer of vegetable fibres (mostly cellulose), connected together in a wet environment and then pressed and dried. Thanks to its easy production, a wide range of raw sources, great variety of types and many properties, paper is a material that is eco-friendly, cheap and easy to produce.

FIGURE 4.1 Shoji (translucent paper screens) and fusuma (sliding panels) in Nazen-ji Temple, built in Kyoto, Japan, in the thirteenth century AD, 2013

In traditional Japanese architecture, paper was used both as a decorative and a functional component. Nowadays, the Japanese architect Shigeru Ban, known as a 'paper architect', has the largest number of works created with paper as a structural material. But shelters and houses mainly made of paper have a longer history. A few chosen examples of realised projects and prototypes are presented below in order to describe the development of paper in architecture throughout the years.

In the first half of the nineteenth century, a shift from artisanal to industrial paper production took place. In 1871 Albert L. Jones in New York invented corrugated cardboard as a packaging material. [6] This invention opened new doors for the paper industry. Between 1874 and 1882, corrugated board with one side glued and with both sides glued was patented in the United States. Soon afterwards, engineers and designers started making the most of this new invention in the paper industry by experimenting with cardboard and corrugated cardboard as building materials.

The first prefabricated houses made of cardboard were exhibited in 1867, at the World Exhibition in Paris. Buildings constructed by the Adt company from Pont-à-Mousson had different functions and dimensions. A summer house had an area of 6x8m, a hospital was 5m wide and 3m high, and a prefabricated house for countries with a tropical climate was 20m long and 5m wide (see Figures 4.2, 4.3 and 4.4). [6]

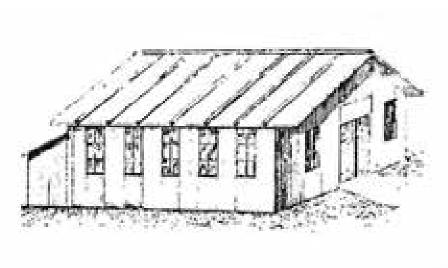

FIGURE 4.2 Prefabricated cardboard house, Adt, 1867

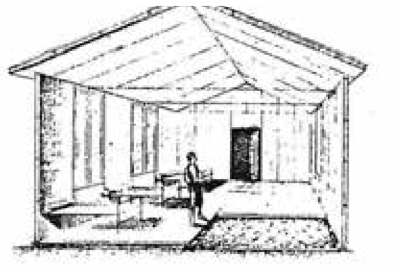

FIGURE 4.3 Cross section of the hospital made out of cardboard, Adt, 1867

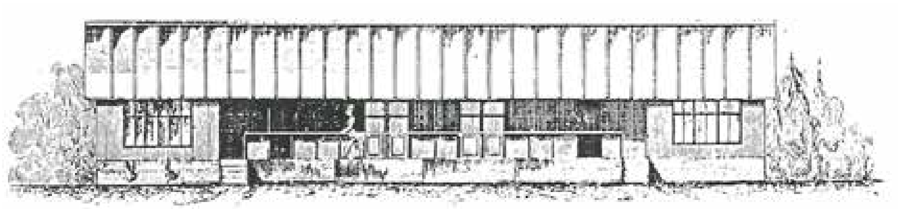

FIGURE 4.4 House for hot countries, made out of cardboard elements, Adt, 1867

The exhibited houses consisted of paper boards that were 3m high and 600-800mm wide, which were connected by means of U-shaped spacers. The construction involved double walls made out of cardboard (4mm thick) on either side of a cavity of 100mm. The hospital weighed about 92 kg per linear metre of the façade. Easily assembled but also easily blown away, it had to be anchored firmly to the ground.

One of the earliest examples of the use of paper in permanent architecture is a house built by mechanical engineer Elis F. Stenman in Rockport, Massachusetts, USA. He started building the summer house as a hobby in 1922. The house was completed in 1924 and Stenman spent all of his summers there until 1930. The house still exists and is open to the public. The structure of the house is a timber framework. The floor and roof were likewise made of wood. The walls were filled with pressed layers of newspaper glued and varnished on the outside. All of the furniture, except the piano and fireplace, were also made out of paper. Although in this case paper was used only as a wall filler, the Paper House is an example of the long-lasting durability of paper, which, with proper maintenance, has been in use for over ninety years now (see Fig. 4.5 and 4.6) [7].

FIGURE 4.5 The Paper House in Rockport, Massachusetts, USA, outer wall 1924

FIGURE 4.6 The Paper House in Rockport, Massachusetts, USA, 1924, detail of the wall

In 1944 the Institute of Paper Chemistry developed an experimental construction of sulphur-impregnated cardboard, which was intended as a portable expandable shelter for a one-year lifespan. The 2.40 x 4.80m large shelter (which only cost $60 and weighed 500 kg) could be set up by one man in an hour (see Fig. 4.7). The walls of the structure were made from waste paperboards formed in 25mm thick corrugated plates, soaked in sulphur and coated with several layers of fireproof paint. These emergency shelters were intended to last one year, but, as Sheppard et al. [8] wrote, were still standing 25 years later. In 1954 the Container Corporation of America, Chicago, developed a dome-like shelter from plastic coated hardboard (see Fig. 4.8). The 24 elements were held together with staples.

FIGURE 4.7 Experimental shelter by the Institute of Paper Chemistry, 1944

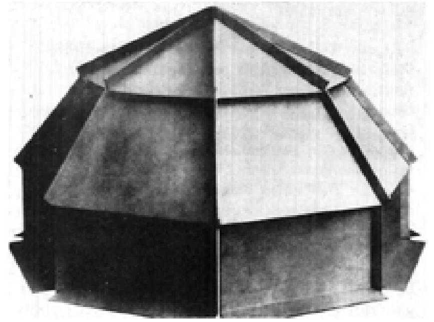

FIGURE 4.8 Container Corporation of America, dome-shaped house made of plastic-coated hardboard, 1954

Richard Buckminster Fuller, a pioneer of many building innovations, won the grand prize of the 1954 Triennale in Milan for a geodesic dome structure made of corrugated cardboard. Students of McGill University in Montreal, led by Richard Buckminster Fuller in 1957, built a construction featuring a geodetic division of space. The dome-shaped building has a diameter of 9.5m and was constructed from only two different standard elements. Those elements, a total of about one hundred pieces, were made of flat cardboard boxes covered on the outside with an aluminium sheet. The plates formed a shell-like outer skin (see Figures 4.9 and 4.10).

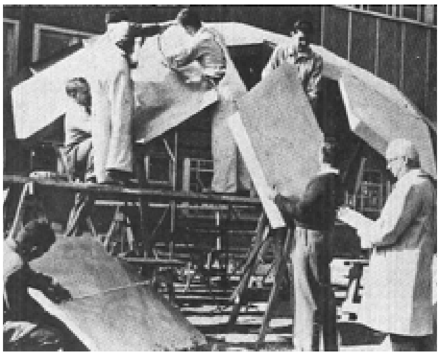

FIGURE 4.9 Construction at McGill University by students and Buckminster Fuller, Montreal, 1957

FIGURE 4.10 Dome shaped building by students of McGill University and Buckminster Fuller, Montreal, 1957

At the Architectural Research Laboratory of the University of Michigan in Ann Arbor, research was carried out between 1962 and 1964 on the use of cardboard laminated with polyurethane foam panels. It focused on the use of foam for the construction of buildings in developing countries. From this material, as well as other materials, frame members were formed with a triangular cross-section. The stress tests conducted on a two-storey test building proved to be sufficient in strength value.

Over one thousand accommodations called 'Plydom' with an anti-prismatic folded plate structure for seasonal farm workers in California were designed and realised by Sanford Hirshen and Sym van der Ryn in 1966. Those foldable units are highly economically sufficient. While open, their dimensions are 5.15x5.80m. The stability of the structure is achieved by parallel folds. The material used was a sandwich panel composed of approximately 10mm thick solid board on both sides with polyurethane foam in between. The board had been made waterproof by means of a polyethylene finish. The total cost of the unit (including heating, evaporative cooling, cooking, washing and complete furnishings) was $1,000 per item [6, 8, 9] (see Fig. 4.11).

In 1967 an experimental polyhedron-shaped construction designed by Keith Critchlow and Michael Ben-Eli was made of corrugated cardboard covered with chicken wire and then sprayed with a thin layer of concrete (see Fig. 4.12). The cardboard plates that were used as a formwork had to be protected from humidity during the concrete-covering process in order to ensure shape stability. The concrete was sprayed on in layers to reinforce and stiffen the cardboard structure before the final layer of concrete was applied.

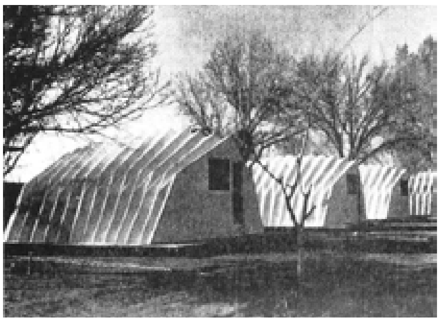

FIGURE 4.11 Plydom – accommodation for seasonal farm workers in California, 1966

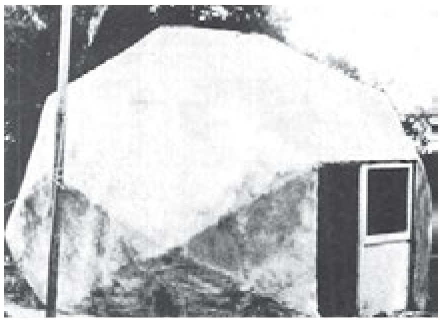

FIGURE 4.12 Experimental polyhedron-shaped structure of cardboard framework covered with concrete, 1967

The project of Baer Zome House features one of the earliest examples of a solar passive house, designed by Steve Baer in Corrales, New Mexico in 1971. The openable sandwich wall panels were composed of 50mm thick cardboard honeycomb panels laminated on both sides with thin aluminium sheets. The entire house consisted of clusters of zomes, whose name comes from a combination of the words 'dome' and 'zones' (see Fig. 4.13). Some of the walls were made of adobe blocks, and those exposed to the south consisted of 56-gallon steel barrels filled with water behind the glass and covered by openable sandwich wall panels to produce warm water. [10]

FIGURE 4.13 Baer Zome house, Corrales, New Mexico, 1971

Hong Lee and John Gibson, on the advice of John Zerning at the Polytechnic of Central London, developed a prototype for a prefabricated emergency shelter in 1974. An improved version of this, featuring three elements taken together, was exhibited in Wales for six months (see Fig 4.14). Similar principles were used by Vince Tickle and Hong Lee for a small student's house built over a car park. Three layers of corrugated board connected by means of bolts or stapling enclosed an area of 7.2x2.4m, with a height of 3.6m. The timber frame installed inside provided the necessary stability and contained a bunk bed on the second level.

At the experimental site of the California Polytechnic State University in San Luis Obispo, California, student proposals for emergency buildings were shown on the occasion of an 'open day' in 1977 (see Fig 4.15).

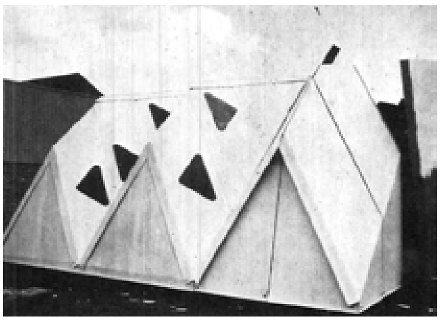

FIGURE 4.14 Hong Lee and John Gibson structure, 1974

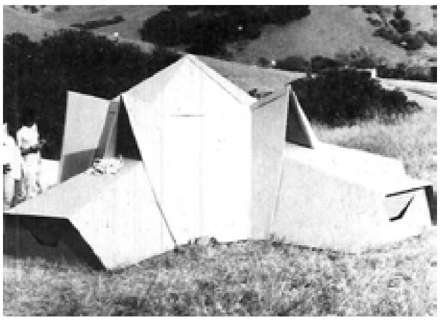

FIGURE 4.15 Emergency building constructed by students of California Polytechnic State University, 1977

Developed by 3H Design (Hübner + Huster) in 1970, Pappedern was an 11.5m^2 or 16m^2 unit composed of 30mm thick corrugated board coated with fibreglass (see Fig. 4.16). Due to the limited lifespan (estimated to be one or two years), 89 units were used at the 1972 Olympics in Munich and Kiel, where they served as recreation and locker rooms, kitchenettes, first-aid rooms and toilets. The units were prefabricated, transported to the site by trucks and installed on the prepared foundations by crane. [6, 11]

In 1975, a 13x18m cowshed-like structure was built at the Instituut voor Mechanisatie, Arbeid en Gebouwen in Wageningen, the Netherlands. Its roof was composed of folded triangular cross-section beams, 9m long and 600mm wide, made of 95mm thick corrugated cardboard coated with polyethylene (see Fig. 4.17). To reduce the formation of condensation inside the cardboard, the cut edges were sealed with special adhesive tape. However, since the polyethylene lamination was not a complete barrier to water vapour, the cardboard was subject to diffusion. As a result, the shed suffered more from the humidity inside the building than from rain.

Another Dutch experiment with cardboard as a building material was an eco-house graduation project carried out by Paul Rohlfs at TU Eindhoven in 1975. After his graduation, Rohlfs received a temporary assignment to build a prototype. Several prototypes were built and examined. The walls of prototype No. 1 consisted of honeycomb panels combined with corrugated cardboard. Prototypes Nos. 2 and 3 were made of honeycomb panels with an exterior breather foil and interior vapour barrier. Prototype No. 4 was inhabited and survived the harsh winter climate of the province of Groningen (see Fig. 4.18). [12, 13]

These paper projects mar ked the end of the 'prehistory' of paper architecture in the 1970s.

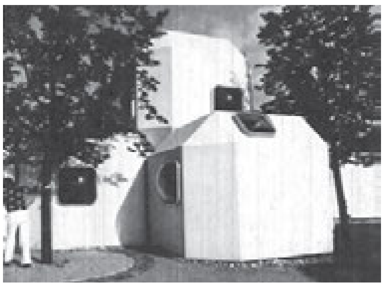

FIGURE 4.16 Cardboard units for the Munich Olympics by 3H Design, 1972

FIGURE 4.17 roof beams made at the Instituut voor Mechanisatie, 1975

FIGURE 4.18 Prototype of a cardboard house by Paul Rohlfs, 1975-1980

§ 4.2 The Modern History of Paper Architecture

In the 1980s, a new era of paper architecture began. It was the Japanese architect Shigeru Ban (born 1957) who had the greatest impact on the promotion of paper as a building material. Ban's adventure with paper in architecture started in 1985, when he was asked to design an exhibition for the architect Emilio Ambasz, who was an Argentinian by birth. He used screens made out of squared in section paper tubes and honeycomb panels cores to organise the exhibition space. In the following year, Shigeru Ban designed an exhibition in remembrance of the famous Finnish architect and designer Alvar Aalto. Both on account of his limited budget and because he wanted to include a reference to wood, which was one of the basic materials used by Aalto, Ban decided to use paper tubes in between the exhibits (see Fig. 4.19). Later, the architect decided to take a closer look at the tubes and examine the possibility of using factory-produced tubes as structural elements in architecture. Tests were carried out to examine the resistance of paper tubes to axial compression, bending and ripping by connecting members, such as screws. Furthermore, Ban carried out examinations of the changes paper underwent as a result of various climatic conditions. In 1991, the results of all this research allowed him to obtain permission for the first permanent construction made of paper tubes in Zushi, Kanagawa Prefecture, and to build Library of a Poet (see: Case Studies, section 4.2.1) .

FIGURE 4.19 Alvar Aalto exhibition designed by Shigeru Ban, 1985

The history of the use of paper in architecture shows a wide variety of experimental approaches. The invention of machine-produced paper, as well as of corrugated cardboard and honeycomb panels, had a significant influence on the development of paper-based structures. Most of the examples presented in this chapter can be categorised as emergency or short-lifespan houses. The housing shortage in America and Europe after World War II was one of the reasons why new materials and applications were given a boost in low-cost housing for immigrants and soldiers returned home from the war. Furthermore, experimental works created in the 1960s by Buckminster Fuller or Keith Critchlow and Michael Ben-Eli encouraged other designers to reach for paper and cardboard as new materials for architecture. Cardboard was used as both the primary and secondary structural material. Starting from 1980, more and more attention was drawn to sustainable materials. Since then, paper has been widely recognised as an eco-friendly material and gained popularity in architectural applications.

The milestone in contemporary paper architecture was Ban's Paper House project, built in 1995. The project was the first structure in which paper tubes were allowed to be used as a structural material for a permanent construction (see: Case Studies, section 4.2.3, Paper House).

The largest construction made of paper tubes was the temporary Japan Pavilion, designed by Shigeru Ban for the World's Fair Expo 2000 in Hanover (see: Case Studies, section 4.2.7). [14]

Over 55 projects designed by Shigeru Ban involved the use of cardboard as an architectural material. The nature of the projects varies according to their function (furniture, exhibitions, pavilions, educational and cultural, and relief buildings), lifespan (temporary and permanent) and specific materials. Most projects featured paper tubes, but sometimes honeycomb panels were used, as well.

In 2014 Shigeru Ban was awarded the Pritzker Architecture Prize, which is often described as the Nobel Prize for Architecture. The jury stated that the architect was presented with this highly prestigious award for his brave formal and functional quest in architecture, using new materials, and for his human and humanistic approach to his profession, among other things. [15]

Apart from Shigeru Ban, there are other contemporary examples of architects from all over the world using paper as a material in spatial structures. The earliest example of a permanent building with cardboard structural elements in Europe is Westborough Primary School in Westcliff-on-Sea, England. The building was an experimental design by Cottrell & Vermeulen Architecture, in association with BuroHappold Engineering, a consultancy and design agency. The social room for children was built in 2001 and is still in use fifteen years later (as of February 2016).

Professor Mick Eekhout, Chair of Product Development in Architecture at Delft University of Technology and founder of a Dutch company called Octatube, cooperated with Shigeru Ban during the realisation of three projects: Demountable Paper Dome for IJburg Theatre in Amsterdam and Utrecht, the Netherlands (2003), the Vasarely Pavilion in Aix-en-Provence, France (2006) and Paper Bridge in Vers-Pont-du-Gard, France (2007). In 2010 Professor Eekhout's son, Nils Eekhout, designed and built a multi-functional extension for the Ring Pass field hockey and tennis club in Delft in the Netherlands, using the Tuball space frame system of Octatube (1983) with cardboard tubes.

A recent innovation in paper architecture is Wikkel House. 'Wikkelen' is Dutch for 'to wrap'. Designed by René Snel in the late 1990s, Wikkel House was further developed by Fiction Factory, based in Amsterdam. In 2012 Fiction Factory bought the copyrights, (re)developed the project and commenced production of these wrapped corrugated board structures.

Impregnation and coating methods proved that many different materials, such as sulphur, fibreglass or polyethylene coating, cladding with another material, sandwiched compositions or spraying concrete on formwork-like cardboard structures, were successful. The ongoing process of experimental use of paper in architecture was provided a boost by new production technologies, new chemical compositions, and by the growth of the paper industry and market.

The aforementioned buildings – both the experimental ones and the ones that were actually realised – show that paper in the form of products such as paper boards, paper tubes and honeycomb panels can be successfully used not only as a part of the construction but as a main load-bearing element. In order to allow us to take a closer look at the structural possibilities of paper-based elements, we will study a few realised examples of contemporary paper architecture below.

By far the most popular cardboard-affiliated product in the built environment is the honeycomb-filled lightweight hardboard door with a timber frame for interior purposes. Millions of these doors have been produced and painted, and they are in regular use in houses and apartments.

The 150-year history of paper architecture shows that paper is an inspirational building material that provides ample potential for novelties waiting to be explored by industries, factories, companies and universities around the world.

§ 4.3 Case Studies of paper in architecture

The following section will provide a closer look at a few selected realised structures, in which paper was used as a main structural material. Each project will be described in accordance to its function, usable area, structural system, composition (walls, roof, floor), details (connection between elements, connection with the ground) and method of impregnation. Fifteen case studies were chosen from the dozens of realised projects featuring paper architecture. The selected projects have distinctive qualities that will guide us to a better understanding of the properties of paper as a building material.

§ 4.3.1 Library of a Poet

Authors: Shigeru Ban Architects
Year: 1991
Location: Zushi, Kanagawa, Japan
Area: 35m² (size: M)
Lifespan: Permanent
Type: Housing

Library of a Poet is a 35m² extension to the House for a Poet, which was enlarged and renovated by the architect two years previously. Library of a Poet is the first permanent building in which paper tubes were used as a structural material. This one-storey building with entresol is composed of six paper tube truss supports which hold an arched roof also composed of paper tubes (see Fig. 4.20). The roof arches are tied with two horizontal paper tube beams post-stressed with steel rods inside (see Fig. 4.21). The paper tubes (100mm in diameter and 12.5mm thick) making up the walls were tested for one year to investigate the phenomenon of creep in different temperatures and relative humidity. A 400mm long specimen was inserted between two plates that were fastened by steel rods at 29 kg/cm², which was one-third of the maximum compressive strength of the paper tubes. For a period of one year, measurements were taken at intervals of about one week. The tests showed that paper tubes deformed depending on the different temperatures and levels of humidity, but deformation due to creep was minimal. The paper tubes were connected by 100x100mm wooden blocks braced with post-tensioned steel rods diagonally and inside of the tubes (see Figs. 4.22, 4.23). The paper tube structure was inside the building, where it was protected from the outside weather conditions by the roof and glazed walls. In other words, the tubes were not exposed to the weather conditions. The structure was placed on a concrete floor slab. The four full-height timber bookshelves were installed independently of the paper tubes on both longitudinal walls. The bookshelves were cantilevered from the floor and absorbed the lateral wind forces. They were also thermally insulated and finished from the outside, and so acted as external walls. This idea was later used by Shigeru Ban in his Furniture House projects. [1, 14, 16]

The structure used to create Library of a Poet was a hybrid structure consisting of paper tube trusses and prefabricated bookshelves. The tubes mostly carried dead loads and vertical loads from the roof, while the bookshelves carried the lateral forces. The combination of the two different structures allowed Ban to use relatively small tubes and connections. The paper tubes were connected by wooden blocks and post-stressed steel bracing, which meant no screw or bolt connections had to be used between the wood and the paper, because paper is quite fragile and will tear easily when used in such connections.

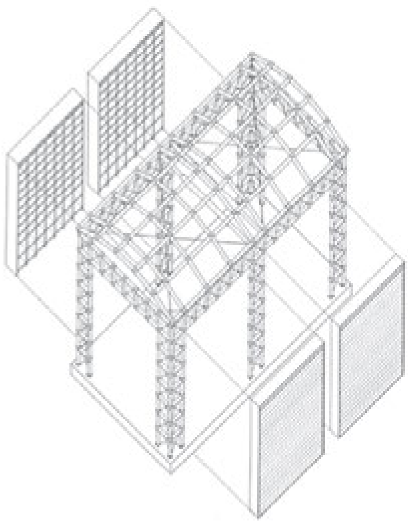

FIGURE 4.20 Exploded axonometric view of the structure of Library of a Poet, 1991

FIGURE 4.21 The library viewed from the inside, 1991

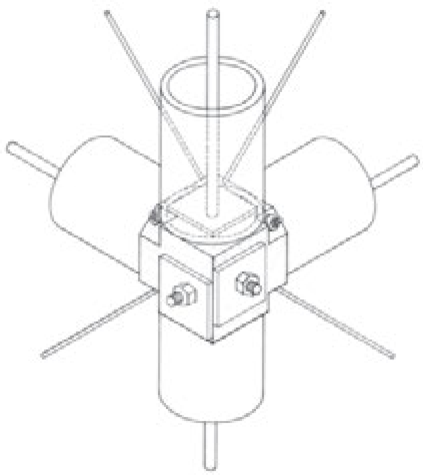

FIGURE 4.22 Axonometric view of a connection detail, 1991

FIGURE 4.23 Photo of a wooden connector of paper tubes and post-stressed steel rods, 1991

§ 4.3.2 Apeldoorn Cardboard Theatre

Authors: Prof. Hans Ruijssenaars, ABT Building Technology Consultants
Year: 1992
Location: Apeldoorn, the Netherlands
Area: 240m^2 (size: L)
Lifespan: Six weeks
Type: Temporary event venue

To mark the 1,200th anniversary of the first settlement of the city of Apeldoorn, Prof. Hans Ruijssenaars was asked to design a temporary theatre. As Apeldoorn is situated next to the Veluwe region, which has quite a tradition of paper production, Ruijssenaars decided to use paper as a material for his temporary theatre. The cylindrical shell that covered the area (12x20.5m) was composed of members made of corrugated board (see Fig. 4.24). Each of the members had a dimension of 1,200mmx350mm and was 35mm thick. It consisted of seven laminated layers of corrugated cardboard. At the end of each side of the member, the hardboard plates used for connections with nodes were laminated. Each node connected six members with a wooden ring and a hose clip. The interlocking connectors required only a hammer and screwdriver to keep the elements together (see Figs. 4.26 and 4.27). The triangular composition of members was covered with plasticised corrugated cardboard plates. The seams between plates were taped off. The whole structure, covered with a stretched canvas membrane that was designed to keep the structure watertight and was anchored to the ground with pegs, also kept the lightweight theatre in place and prevented it from being blown away (see Fig. 4.25). The canvas was kept away from the cardboard plates by the membrane stretched between the tops of the nodes. The semi-cylindrical theatre was placed on prefabricated concrete slabs. The bottom nodes were connected with timber beams by 50x6mm steel plates (see Fig. 4.29). The total weight of the 240m^2 theatre, which was able to accommodate up to 200 visitors, was 1,500kg. The structure was used for six weeks, i.e., not long enough for the impregnated cardboard elements to be weakened by moisture from humid air creeping into the material. [13, 17, 18]

Because the structure was mostly made of cardboard rather than other materials, the Apeldoorn Cardboard Theatre was a temporary structure that generated little construction waste after the end of its lifespan. The simple connections between the structural elements and their lightness made the construction a basic one. As the Theatre was only ever supposed to be used for six weeks, the construction elements were not impregnated. However, for a longer lifespan, corrugated members could be coated or wrapped with a layer polyethylene film or plastic foil to create a functional decoration.

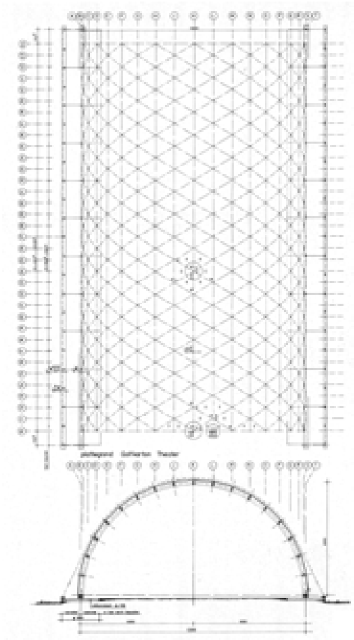

FIGURE 4.24 Plan and section of Apeldoorn Cardboard Theatre, 1992

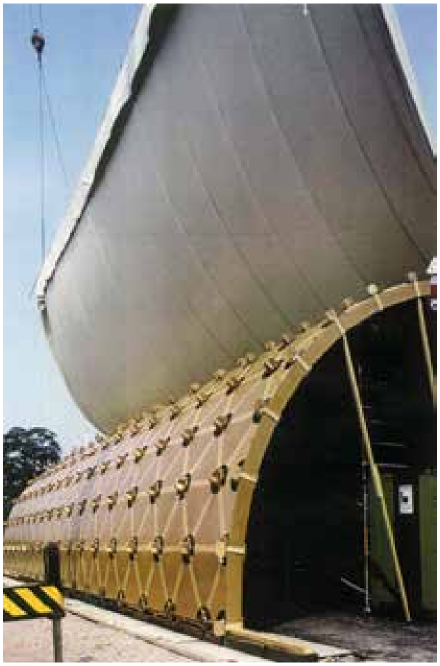

FIGURE 4.25 Watertight membrane covering the cardboard structure with a separate canvas membrane from the top downwards , 1992

FIGURE 4.26 Connection between cardboard member, 1992

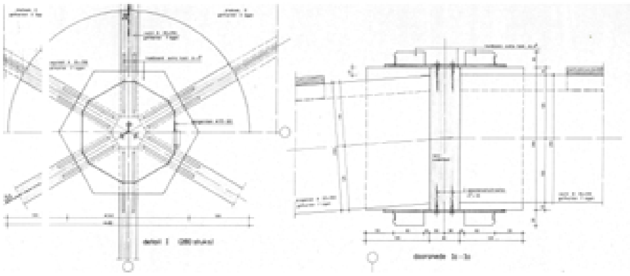

FIGURE 4.27 Details of connections between members

FIGURE 4.28 View of the inside of the theatre, 1992

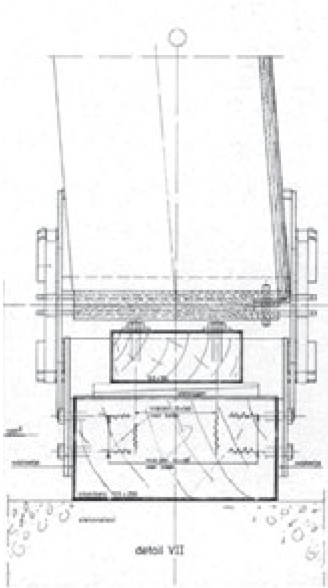

FIGURE 4.29 Detail showing how the members were connected to the ground, 1992

§ 4.3.3 Paper House

Authors: Shigeru Ban Architects
Year: October 1990 to July 1994; construction: October 1994 to July 1995
Location: Lake Yamanaka, Yamanashi, Japan
Area: 100m² (size L)
Lifespan: Permanent
Type: Housing

The architect's own summer house is the first permanent construction ever in which paper tubes were allowed to be used as a structural material. The Paper House is composed of 110 paper tubes, which by an S-shape arrangement divide the living space, circulation area, bathroom and small garden (see Fig. 4.3). The boundaries of the house are demarcated by a 10x10m² large roof area and enclosed by sliding glazed panels which are a reference to traditional shoji panels. The circular living area lacks furniture, except a kitchen counter and movable closets (see Fig.4.31). The interior can be divided into separate rooms by sliding walls for a private area and living space. The purity of the building is accentuated by the horizontal lines of the roof and the floor, and the vertical lines of the paper tubes (see Figs. 4.30 and 4.33). In the gallery circling the living space, a paper tube (1,270mm in diameter) functions as a toilet and a single tube (280mm in diameter) marks the entrance to the house. A smaller circle consisting of 29 externally placed tubes comprises the bathroom and the garden. A total of eighty paper tubes with an external diameter of 280mm (15mm thick and 2,700mm long) are placed inside the building. Ten of the tubes carry the vertical forces from the roof and 80 tubes carry the lateral stress on the structure caused by wind and earthquakes. Although the forces are different in the vertical and lateral directions, all the paper tubes are the same size in order to preserve the purity and elegance of design. Each of the tubes is connected, as they are cantilevered from the floor, to timber cross-shaped connection by means of twelve lag screws. Timber connectors are anchored to the foundation. In October and November 1991, prior tests on paper tubes were conducted at Waseda University in Tokyo. The short-term strength of the paper tubes was tested to determine whether they could withstand bending and axial compression and whether they were strong enough for a wood-to-paper connection by log screw. As humidity also plays an important role with this kind of material, the moisture content was also measured. The average moisture content of the material was 8.8 percent. Tests showed that bending strength was 161.3 kg/cm^2 and compression 113.9 kg/cm^2. In 2013, during a conversation at Kyoto University of Art and Design, Shigeru Ban informed Jerzy Latka that the Paper House built eighteen years previously was still standing and that the paper tubes were in good condition. However, the building was barely used as Ban lived either out of a suitcase or in Paris, and some elements of the structure, such as the concrete feet, had cracked with time. [1, 14, 16]

FIGURE 4.30 Paper House, 1995

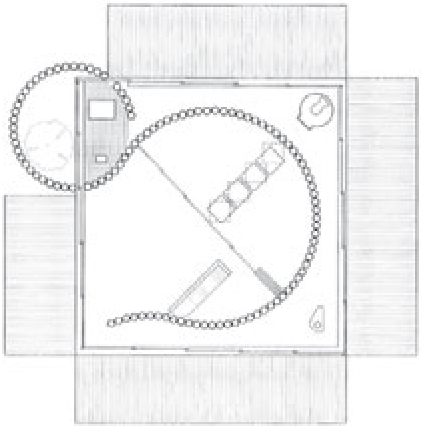

FIGURE 4.31 Floor plan of Paper House, 1995

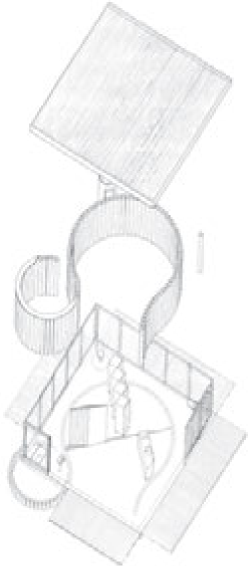

FIGURE 4.32 Exploded axonometric view of the structure of Paper House, 1995

FIGURE 4.33 iew from the inside of Paper House, 1995

§ 4.3.4 Paper Log House

Authors: Shigeru Ban, VAN
Year / Location: August 1995, Kobe, Japan; January 2000, Kaynasli, Turkey; September 2001, Bhuj, Gujarat, India; 2014, Daanbantayan, Cebu, the Philippines
Area: 16m^2 (size M)
Lifespan: Temporary
Type: Emergency shelter

In the year of 1995 Shigeru Ban started the Voluntary Architects' Network, a non-governmental foundation whose aim is to build aid facilities for the victims of natural disasters or disasters caused by human activity. The VAN Foundation's activities focus on research and the design and erection of emergency buildings. The volunteers engaged in the organisation are mostly students of Shigeru Ban's, as well as students and architecture professionals who come from different parts of the world to participate in the projects. [19]

The first emergency building constructed by Ban and VAN was Paper Log House. It was designed for the Vietnamese community living in Japan that lost their homes during the Great Hanshin-Awaji Earthquake in Kobe in 1995. Paper Log House (see Fig. 4.34) has a ground floor area of 6x6m. Its structure was made of paper tubes with a diameter of 108mm and a thickness of 4mm, placed next to each other and connected to each other with self-adhesive sponge tape. For additional support, steel rods were placed horizontally into the cardboard tubes. The walls were attached to the floor boards by means of wooden pegs. The base board was set on foundations made of beer crates and filled with sand bags (see Fig.4.38). The roof was covered with a PVC membrane stretched on a frame made of paper tubes. The roof's gables could be opened during the summer to get an air flow (see Figs.4.36 and 4.37). The construction of the Paper Log House was simple and could be managed by non-professionals. After the house had been erected, the paper tubes were painted with a polyurethane-based varnish. The cost of one unit built in Kobe was approximately USD 2,000 and it took a group of two to four volunteers six hours to erect it. Twenty-seven Paper Log Houses were built in Kobe in 1995. The shelters were also put up in other parts of the world. Seventeen units were constructed in Turkey in 2000, twenty units in India in 2001 and a few units in Daanbantayan in the Philippines in 2014. Both the Turkish and Indian solutions differed slightly from the original Kobe houses. Because Turkish families tend to be larger, the Turkish Log Houses were 3x6m. In Turkey the paper tubes were filled with waste paper for improved thermal insulation. Lack of beer crates in India resulted in the foundations being built out of rubble left over from destroyed buildings, covered with a layer of soil flooring. The roof vaults in India were made out of cane mats with a tarpaulin placed on bamboo ribs. The veranda added to the house offered a shaded outer space (see Fig. 4.35). The most recent version of the Paper Log House was built in 2014 in the city of Daanbantayan, the Philippines. This time round, paper tubes served only as a frame structure covered with locally produced bamboo-mat walls, which allow air and light to pass through. The Philippines project was based on the idea of Paper Partition System No. 3, i.e., lightweight partitions as developed by Ban in 2006. The Paper Log Houses, built from recyclable and locally sourced materials, minimalised the problems of waste left over after usage. [1, 14, 19, 20]

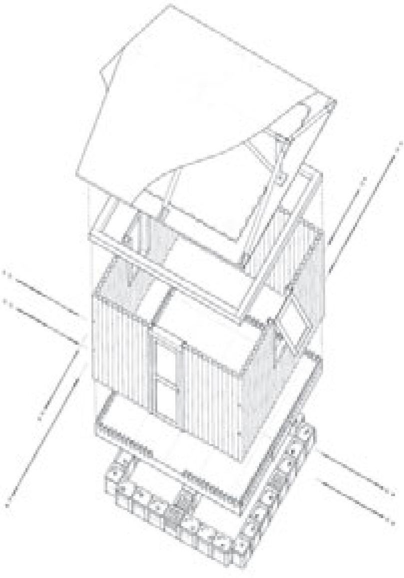

FIGURE 4.34 Paper Log House in Kobe, Japan – exploded axonometric view, 1995

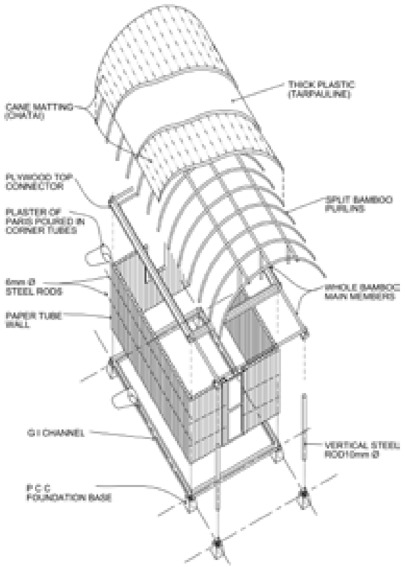

FIGURE 4.35 Paper Log House in Bhuj, India – exploded axonometric view, 2001

FIGURE 4.36 Paper Log House at an exhibition in Mito, Japan, 2013

FIGURE 4.37 Paper Log House at an exhibition in Mito, Japan, view from the inside, 2013

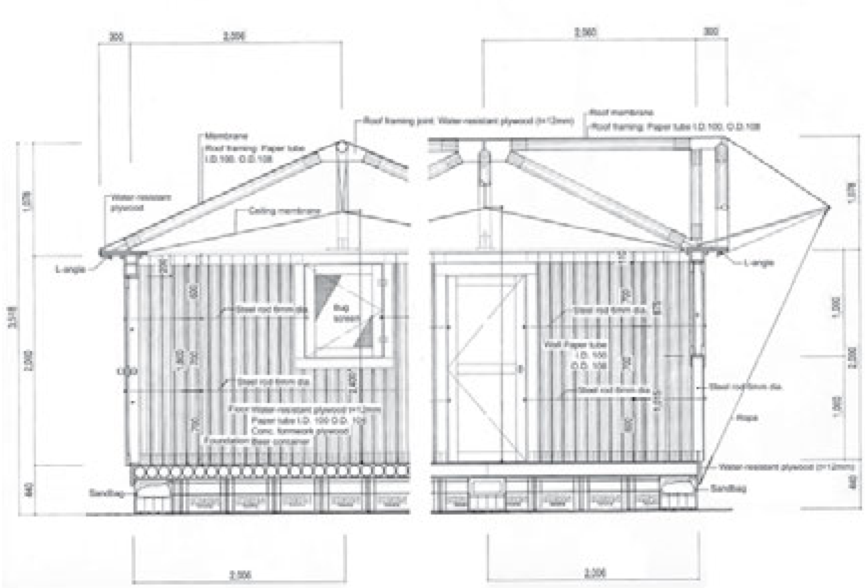

FIGURE 4.38 Paper Log House in Kobe, Japan – detailed section, 1995

In the same year in which the Paper Log Houses were built in Kobe, Shigeru Ban, in association with 160 volunteers from all over Japan, built the Takatori Paper Church for the Vietnamese community. The outer skin of the church was installed on a rectangular area of 10x15m and enclosed by polycarbonate sheeting. The interior of the church, whose elliptical plan made reference to Italy's seventeenth-century Bernini-designed churches, was created out of 58 paper tubes, 330mm in diameter. The walls were 15mm thick and 5m high. The roof of the church was made of tent material. After ten years the Paper Church was dismantled in June 2005 and rebuilt in Taiwan in 2008 (see Fig. 4.39). [16]

FIGURE 4.39 Paper Church in Kobe, Japan, 1995

§ 4.3.5 Paper Arch Dome

Authors: Shigeru Ban Architects, Van Structural Design Studio
Year: 1998
Location: Masuda, Gifu, Japan
Area: 445m^2 (size: L)
Lifespan: Permanent
Type: Workshop

This arch structure was built as an extension to an open-air wood-working place, to be used particularly during the winter. The structure covers an area of 22.8x27.8m^2 (see Fig. 4.40). The aim of the project was to create a simple structure, possibly to be built by a team of carpenters rather than professional construction workers. The structure of a single arch consists of eighteen 1.8m long paper tubes with an internal diameter of 250mm and walls 20mm thick (see Fig. 4.41). The tubes were connected through laminated timber joints by means of lag screws (see Fig.4.44). Timber joints formed the shape of the arch, while the paper tubes remained straight. The top height of the arch is 8m. Nineteen arcs were interconnected by horizontally placed paper tubes with a length of 0.9m, internal diameter of 130mm and walls 5mm thick. For lateral stiffness, the paper tube arcs were covered with structural plywood. Each panel contains a hole with a 500mm diameter to allow natural light to enter. Translucent corrugated polycarbonate panels were placed on top of the plywood (see Fig. 4.45). Additional steel rod bracing was used for stability to allow for sudden load changes, caused, for example, by great amounts of snow falling from the roof.

The whole structure was fixed on concrete foundations that began the curvature of the arch. On the bottom part of the arch extra paper tubes were installed in order to stiffen the structure and to take the bending moments from the connection with foundations (see Figs. 4.42 and 4.43). As the structure was subject to changing weather conditions, the paper tubes were covered in advance by pure polyethylene for protection against humidity. In spite of the fact that paper tubes had been accepted as a building material for the Paper House project, Shigeru Ban had to conduct more tests to prove the stability of the structure.

The test conducted to assess the compression and bending strength of paper tubes showed that compressive strength decreased in an inverse ratio to the rise in moisture content. Ninety-five specimens of paper tubes with an outer diameter of 95mm and walls 5mm thick and a length of 259mm were tested under different moisture conditions. Up to the 7% moisture content level, the paper tubes retained their compressive strength. Then between 7% and 13% their strength gradually decreased, and once the moisture level exceeded 13%, the strength of the tubes was clearly compromised. [1, 16]

The tests confirmed the beneficial collaboration of paper and wood when the two materials were connected. [14]

The idea of Paper Dome structures was later employed in other Shigeru Ban projects: Paper Studio at Keio University (2003), Paper Temporary Studio on the sixth floor roof terrace of the Centre Pompidou in Paris (2004), and Shigeru Ban Studio at Kyoto University of Art and Design (2013).

FIGURE 4.40 Paper Dome, 1998

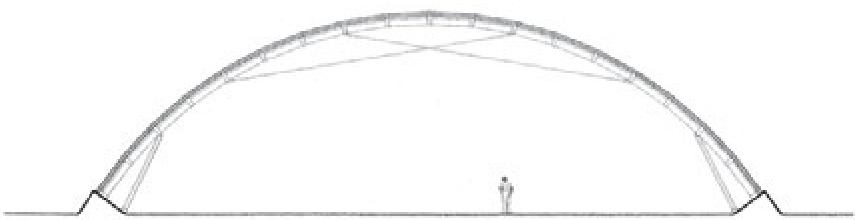

FIGURE 4.41 Paper Dome – section, 1998

FIGURE 4.42 Paper Dome – connection with the foundation, 1998

FIGURE 4.43 Paper Dome –connection between paper tubes, 1998

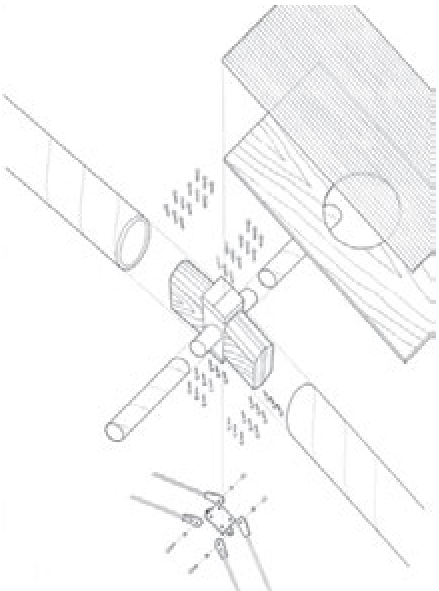

FIGURE 4.44 Paper Dome – detail of the connection between the paper tubes and timber joints, 1998

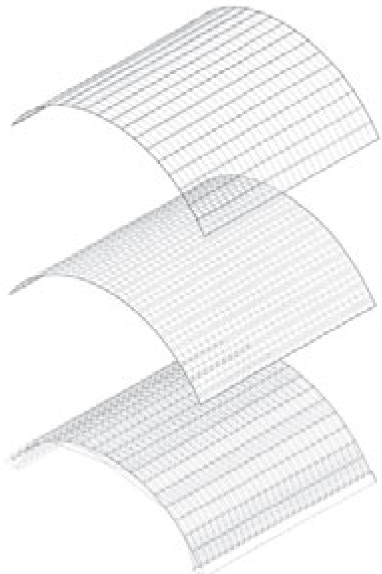

FIGURE 4.45 Paper Dome – layers of the structure, 1998

§ 4.3.6 Nemunoki Children's Art Museum

Authors: Shigeru Ban Architects
Year: 1999
Location: Kakegawa, Shizuoka, Japan
Area: 320.2m² (size: L)
Lifespan: Permanent
Type: Public building

FIGURE 4.46 Nemunoki Children's Art Museum, 1999

In his project Nemunoki Children's Art Museum, realised in Kakegawa, Japan, in 1999, Shigeru Ban applied the lattice made of panels with a honeycomb structure as a lightweight stiffening and strengthening element of the roof construction (see Fig. 4.46). The lattice structure is similar to the one used as the gable walls in the Japanese Pavilion in Hannover. Honeycomb panels used as a roof structure were covered with translucent PVC and also served as caissons to prevent direct sunlight from penetrating from above (see Fig. 4.50). The product used in the construction of the museum was not a typical honeycomb panel, which is created by gluing the top and bottom surface with the honeycomb grid in between. The grid-core panels used in the Museum were composed of two moulded sub-panels opened from one side. Two sub-panels were then glued together, creating much stronger material. The structure of the roof lattice was based on an equilateral triangle, with walls 3,000mm long and 600mm high (see Fig. 4.47). This basic unit was stiffened by a 1,000mm triangular division inside.

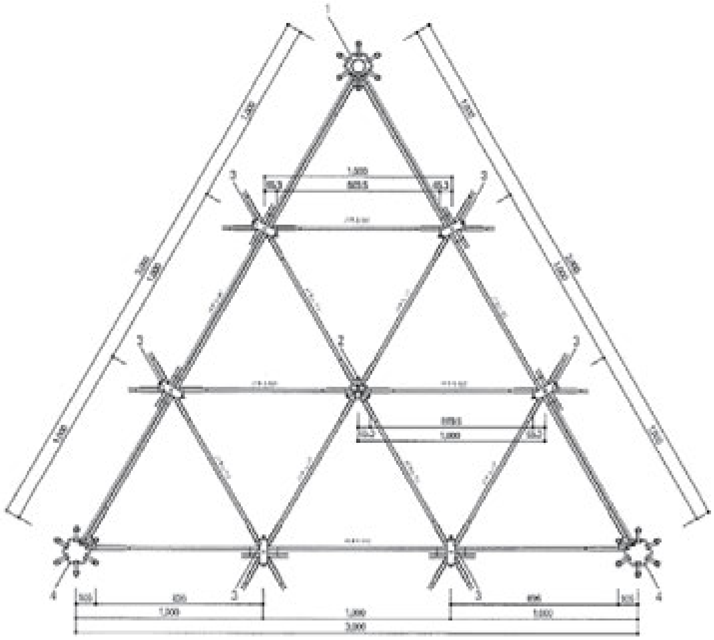

FIGURE 4.47 Nemunoki Children's Art Museum – grid-core cardboard lattice scheme, 1999

The honeycomb panels were connected by aluminium plates to form 60° triangles. The plywood boards were placed inside the honeycomb panels to reinforce the bolt connection with aluminium plates (see Figs. 4.51 – 4.55).

The roof lattice with triangular pattern was connected by four types of aluminium joints:

- The joints that connect six boards to a hexagonal die-cast pipe that was connected with the pillar.
- The joints that connect the 3,000x600mm honeycomb grid-core panels from two directions.
- The joints that attach six 1,000x600mm honeycomb panels to a triangular die-cast pipe with a 60° angle between.
- The joints that connect six boards to a hexagonal die-cast pipe.

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The whole structure of the roof was composed of 64 triangular basic units whose walls were 3,000mm long. The use of a roof structure based on a triangular grid allowed the architect to use limited types of connections and to create a lightweight and rigid planar structure. Fully glazed walls and translucent PVC covers over the roof protect the grid-core panels from the impact of the weather (see Figs. 4.48 and 4.49). The climate-controlled interior of the Nemunoki Museum assumed an interior temperature of 20°C and relative humidity of 60%. In September and October 1998 a series of tests on grid-core panels was conducted. The panels were tested for tension, compression, bending moments and adhesion strength between plywood and grid-core panel skins. The tests were carried out at different levels of humidity (60% and 90%). Tests showed that the grid-core panels had a 9.5% moisture content at a relative humidity level of 60%, and a moisture content level of 15.8% at a relative humidity of 90%. At the same time, the compression strength of the panel with a moisture content of 15.8% dropped to 61% compared with the compression strength of the panel with a water content of 9.5%.

Honeycomb panels are more resistant to the equally distributed forces perpendicular to the plane. Thus a combination of corrugated boards with corrugation in the vertical direction and honeycomb panels could increase stiffness in both the vertical and lateral directions.

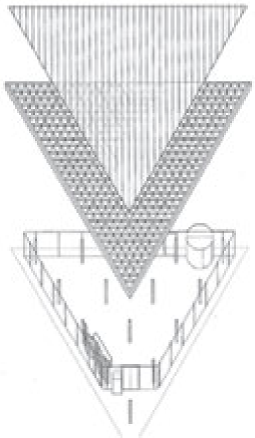

FIGURE 4.48 Nemunoki Children's Art Museum – exploded axonometric view, 1999

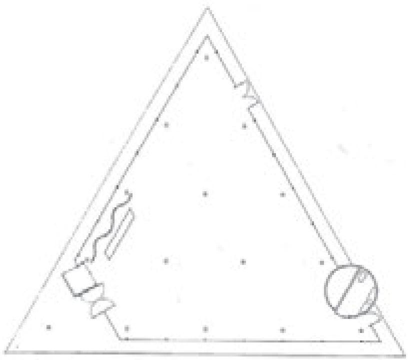

FIGURE 4.49 Nemunoki Children's Art Museum – plan view, 1999

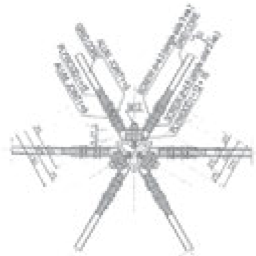

FIGURE 4.50 Nemunoki Children's Art Museum – detail of the roof structure, 1999

FIGURE 4.51 Nemunoki Children's Art Museum – aluminium connectors, 1999

FIGURE 4.52 Nemunoki Children's Art Museum – aluminium connectors, 1999

FIGURE 4.53 Nemunoki Children's Art Museum roof structure and construction, 1999

FIGURE 4.54 Nemunoki Children's Art Museum, construction of the roof, 1999

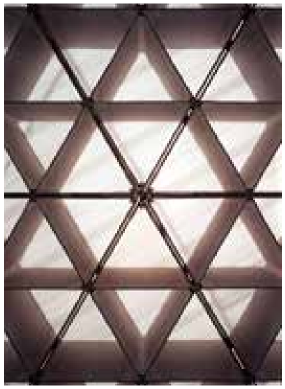

FIGURE 4.55 Nemunoki Children's Art Museum, grid-core cardboard lattice roof, 1999

The honeycomb structure used in the Nemunoki Children's Art Museum was authorised by Japan's Minister for Construction and has been approved for use in Germany, as well.

§ 4.3.7 Japan Pavilion, World Expo 2000, Hannover

Authors: Shigeru Ban Architects
Consultant: Prof. Frei Otto; Structural engineer: BuroHappold; General contractor: Takenaka Europe GmBH
Year: 2000
Location: Hannover, Germany
Area: 3,090m² (size: XL)
Lifespan: Five months
Type: Temporary event venue

FIGURE 4.56 Japanese Pavilion for Expo 2000 in Hannover

The idea behind the design for the Japan Pavilion at Expo 2000, held in Hannover, was to build the structure from recyclable materials to the maximum extent possible, in response to the theme of the Expo: 'Humankind - Nature - Technology: A New World Arising'. Also, ideally it should only barely touch the ground, so as to reduce the footprint left following the demolition of the pavilion.

FIGURE 4.57 The interior of the Japanese Pavilion at Expo 2000 in Hannover

The building, which measured 74x25m and was 16m high, was constructed in the form of a three-dimensional grid shell with indentations along the length of the structure (see Fig. 4.56). The tension between paper tubes obtained by raising the flat structure turned the tubes in a gentle and curvilinear manner that provided sufficient strain to support the structure. The double curved one-metre grid shell was composed of 440 continuous cardboard tubes whose diameter was 120mm and whose walls were 22mm thick, covered with acrylic varnish (see Fig. 4.57). The size of the tubes was determined by the curvature of the whole structure. One hundred and twenty millimetres was the maximum diameter that allowed tubes to be bent to a required 10m radius of curvature. The project involved the use of paper tubes created to 'infinite' length by means of spiral winding. The tubes were fabricated to a twenty-metre length for transport, then connected to wooden inserts. The paper tubes set on the one-metre diagonal grid were connected with fabric tape to allow three-dimensional movement and rotation of the tubes during the erecting process. Due to the risk of paper tube creep over time, the structure was strengthened with arcs in the form of laminated timber ladders with rafters running longitudinally along the structure. The laddes were composed of doubled 60x75mm timber members with some distance in between. A continuous horizontal purlin measuring 60x95mm was fixed between the members of the ladders (see Fig. 4.59). Laminated timber laths created a grid of approximately 3x3m. Additionally, 8mm thick stainless steel cable bracing was fixed to the timber ladders with steel straps. The arc ladders facilitated covering of the external surface of the building. The inner membrane was composed of five layers of flameproof polyethylene, non-combustible paper and a glass-fibre fabric in the middle. The outer membrane was made of transparent polyester fabric coated with PVC (see Fig.4.58).

FIGURE 4.58 Exploded axonometric view of the Japan Pavilion, 2000

FIGURE 4.59 Detail of the connections between the paper tube lattice and timber ladder, 2000

FIGURE 4.60 Detail of a gable wall, 2000

The semi-circular gable walls were bookended by two timber arches clamped to the ends of the paper tube grid shell. The gable walls were composed of triangular panels made from plywood, honeycomb cardboard panels and paper membrane (see Fig. 4.60). They were constructed like a tennis racket, with cables at a 60-degree angle from the foundation. The foundations of the building were made of A-shaped steel frames located under each of the arc ladders. The frames were fitted with timber boards and filled with sand. At the foundations and at the end of the arches paper tubes were joined with screws. The structure was erected by elevating the flat grid previously placed on the Peri scaffolding system.

The tubes produced by Sonoco were tested at Dortmund University in order to get more information about the long-term structural performance of the material. The chosen safety factor was similar to EC5 for timber structures, i.e., safety factor γ= 4.

Tests were conducted to assess short- and long-term axial compression and short- and long-term bending moments. Furthermore, an axial compression test was performed after the assembly simulation to check if the paper tubes would lose their strength following adjustment of their curvature. Following the assembly simulation test, specimens with a length of 1,000mm were cut and tested for respective compression strength. No irreversible loss in the strength of the material was detected in the test. In order to check the impregnation with acrylic paint, the paper tubes were tested for compression after being exposed to a weathering cycle. Five specimens were subjected to a seven-day test following the following procedure: on Days 1-5, specimens were subjected for three hours to a temperature of 70°C and 15% humidity, and to rainfall for one hour. On Days 6 and 7, specimens were subjected for two hours to a temperature of 15°C, 15% humidity and a frost-defrost cycle without any rainfall at temperatures of -20°C and +50°C. After a week's exposure, the specimens were tested for compression and bending. The tests showed that neither the bending nor the compression strength of the specimens changed, compared to fresh specimens.

At the Institute for Building Materials, Concrete Structures and Fire Protection, the paper membrane provided by TSP Taiyo was tested for fire protection performance. The paper membrane, which was composed of flameproof polyethylene film, a non-combustible 'OK Cosmo' paper layer, glass-fibre fabric, a non-combustible 'OK Cosmo' paper layer and flameproof polyethylene film, was conditioned to standard atmosphere for two weeks. Five specimens were exposed to flames for fifteen seconds. The tests showed that the examined material should be designated as standard inflammable Class B2. Although the provided incombustible paper passed the tests, due to the possibility that the Pavilion might become a target for a terrorist attack, an additional layer of PVC membrane meeting the Class B1 incombustibility standards was required. Unfortunately, the Japan Pavilion was demolished after use, instead of being recycled. [1, 14, 16]

The Japan Pavilion was a milestone in paper architecture. All the structures realised in Hannover had to fulfil the strict requirements of the German Building Code, even if they were only used for five months. As the structural engineers from BuroHappold concluded in their publication The Japan Pavilion for the Hanover Expo 2000, the Paper Pavilion 'was a stepping stone in the development of paper architecture and has led to further structures being constructed elsewhere in the world'. [21, 22]

§ 4.3.8 Westborough Primary School, UK

Authors: Cottrell & Vermeulen Architecture
Structural engineer: BuroHappold; General contractor: Takenaka Europe GmBH
Year: 2001
Location: Westcliff-on-Sea, Great Britain
Area: 90m^2 (size: M)
Lifespan: Semi-permanent (twenty-year lifespan)
Type: Public building

Westborough Primary School was the first permanent paper structure built in Europe. The building was an experimental design by Cottrell & Vermeulen Architecture in cooperation with Buro Happold Engineering. A social room for children was built in 2001 and is still in use fifteen years later (as of February 2016).

The building was designed for a twenty-year lifespan and its primary aim was to reduce the environmental impact of building materials by using cardboard (a recyclable material) as a main structural and cladding component. The area of the building is 90m^2 and it serves as an 'after-school club' that has its own open space, toilets and service room (see Fig. 4.61).

FIGURE 4.61 Westborough School, South façade, 2001

The structure of the building consists of two kinds of elements: paper tubes and sandwich panels. Two inner walls are composed of eleven paper tubes standing next to each other, which carry the timber truss structure of the roof. Another seven paper tubes were placed in a row, at intervals. These take the loads from the roof, on the side where a big opening for the sliding doors in the northern wall appears (see Fig. 4.62).

The wall and the roof panels are a layered composition of four alternating full cardboard panels 4mm thick each and three honeycomb panels 50mm thick each (see Fig. 4.63). The layers of the panels were fitted into a timber frame and laminated together. The size of the panels was limited by the production process to a maximum height of 2.7m and a width of 1.5m. To minimise the risks posed by moisture and contact with water, the panels were covered with a poly-coated layer on the inside and waterproof building paper on the outside (see Figs. 4.64 and 4.65). Thanks to the vapour barrier on the inside and the breathable water barrier on the outside, the flow of the water vapour into the cardboard was minimised and the vapour was allowed to escape from the cardboard. Full board cardboard protects the inside of the panels. Since cardboard is a relatively fragile material, the final outer layers of the wall and roof panels were additionally covered with 16mm fibreboard-cement panels to prevent them from being damaged by playing students, hail or rain. Eight different types of panels were produced for the folded plate construction forming the wall and roof of Westborough Primary School. [23]

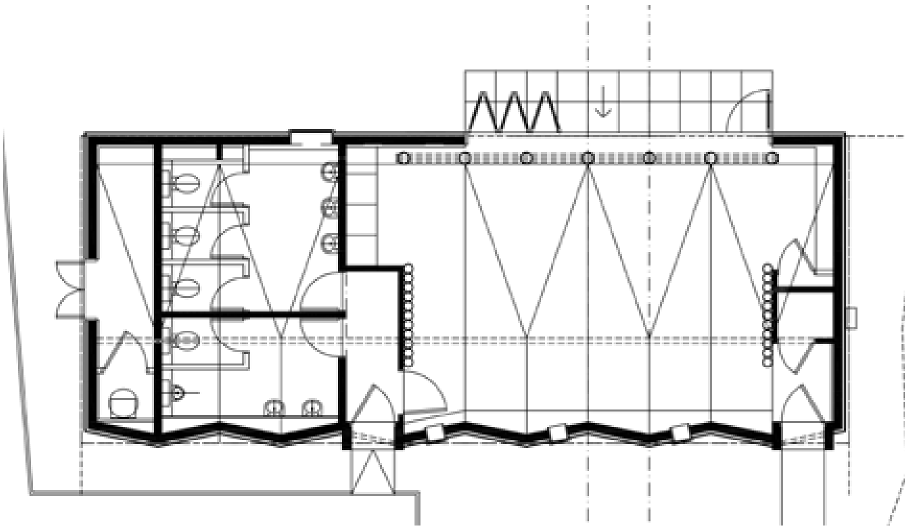

FIGURE 4.62 Westborough School, plan view, 2001

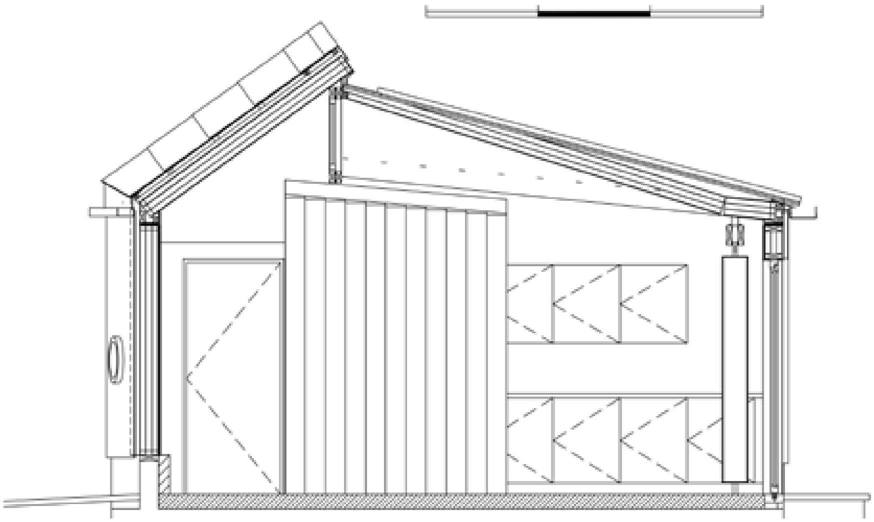

FIGURE 4.63 Westborough School, section, 2001

The joints used between the cardboard elements in both columns and panels were prefabricated wooden elements glued to the cardboard (see Figs. 4.66 and 4.67). The wall and roof panels were simply connected by timber frames which only required a few screws to keep in place. All the exposed surfaces received a fire treatment in order to reduce the risk of damage

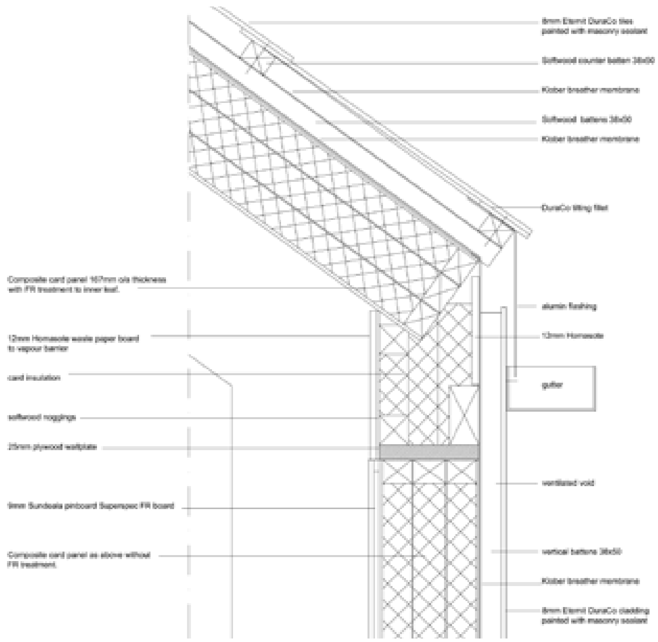

FIGURE 4.64 Westborough School, detail of connection between the wall and the roof panels at the eaves of the building, 2001

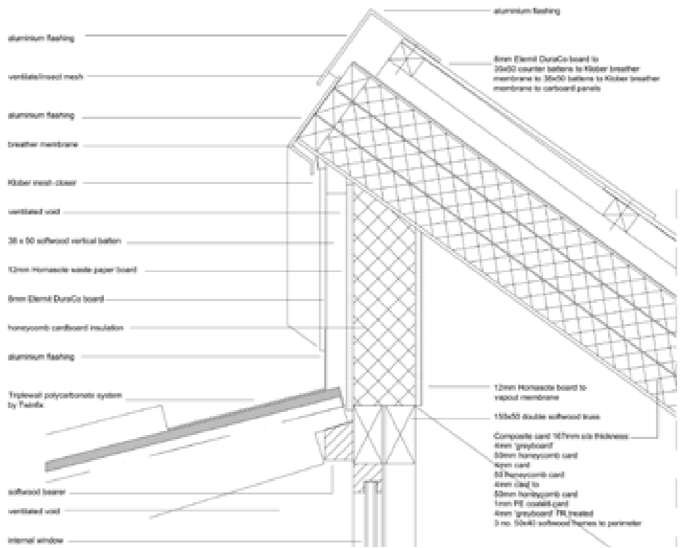

FIGURE 4.65 Westborough School, detail of connection between the wall and the roof panels at the ridge of the building, 2001

FIGURE 4.66 Westborough Primary School, paper tubes structure at the northern side of the building, 2001

FIGURE 4.67 Westborough Primary School, detail of connection between the wall and the roof panels, 2001

The main goals of the project were to prove that cardboard can be used as a full building material, which can be recycled after the lifespan of the building. The assumption was that 90% of the used material would be both recycled and recyclable after use. [23]

Before the final erection of the building, a 6x2.4m^2 prototype was built in order to check buildability and to see how easy it was to connect the building components. During the construction of the prototype, several details of the walls and roof were checked and improved.

BuroHappold conducted a series of tests of water and fire resistance, strength, creep and durability. These tests indicated that a factor of 10% of the compressive strength should be applied in order to avoid the creep of material. They also indicated that structural paper tubes should be protected from moisture and significant changes in temperature, and that a water- and fireproof layer should be applied.

Fire tests carried out for the project showed that 5mm thick untreated full cardboard subjected to a flamethrower charred rather than burned, thus creating a natural fireproof barrier. The tests only just failed the requirements for a Class-1 flame spread.

Four months after the building was erected, some deformations in the paper tubes were detected. The tubes supporting the timber truss were fixed in one position. Lateral movement at the top of the wall was caused by the drying-out of paper tubes, which changed their dimensions. Internal partition walls were installed in order to stiffen the outer walls and no more movement was noticed. Furthermore, a deflection of about 10-15mm was noticed on drying paper tubes.

As A. Cripps mentions in his report, [23] there was ‘other risk [that] included the possibility of not receiving planning permission, building control approval or insurance for the completed building, or that the building might fail at some point during construction or the planned lifetime.’

As the project was a prototype and experiment, the costs of the entire structure were rather high, amounting to £142,042 (€167,610), excluding research and design (which probably added another £80,000). However, the cost can be significantly reduced by serial or even mass production of the elements. Finally, the building showed that the goal of having a building consist of 90% recycled and recyclable material could not be attained. In terms of weight, the concrete foundation made up 85 tonnes out of the total 100-tonne weight of the building. In terms of volume (m^3), cardboard accounted for about 29% of the structure, or 56% if the concrete floor slab was not included. [23]

The paper building of Westborough Primary School was granted a number of awards (2002 RIBA Award, RIBA Stephen Lawrence Prize, 2002 RIBA Journal Sustainability Award, 2002 Civic Trust Awards Commendation).

§ 4.3.9 Demountable Paper Dome (IJburg Theatre), Amsterdam, Utrecht

Authors: Shigeru Ban Architects; associate architects: STUT Architecten; system designers, engineers and general contractor: Octatube
Year: 2003 (Amsterdam); 2004 (Utrecht)
Location: IJburg, Amsterdam; later re-erected in Utrecht, the Netherlands
Area: 485m^2, 26m diameter (size: XL)
Lifespan: Nine years (dismantled in Utrecht in May 2012)
Type: Public building

The Paper Dome was designed by Shigeru Ban for Jeannette van Steen’s mime group. As the client was a mime group, acoustics did not play a role in the design of the building. In the spring of 2003 the dome was erected in the sandy and bare environment of IJburg to stimulate the realisation of this new town. In 2004, the Dome was dismantled and re-built in Leidsche Rijn, near the city of Utrecht. The Paper Dome hosted various social and cultural events for the new town and accommodated 225 seated visitors or 700 standing visitors at a time.

Prior to the design of the details, the fundamental research and development of the material, which took four months, was conducted by the company Octatube, guided by the Chair of Product Development of TU Delft's Faculty of Architecture and the Built Environment and remotely supported by TU Delft's Cardboard research group, led by Prof. Fons Verheijen. No information was available about any previous projects, so Octatube had to start from scratch.

The research focused on the relation between strength and humidity, elastic modulus, buckling and bending strength. Tests conducted in November-December 2002 and January 2003 showed that paper tubes produced by both spiral and parallel winding were not strong enough for the project. The tested specimens had an external diameter of 150-200mm, and their walls were 15-20mm thick. It was noted that they were highly sensitive to moisture, thus resulting in creeping of the material. After four months' research, the American company Sonoco delivered the right paper tubes, which were made of virgin fibres, unlike the previous ones, which were made of recycled paper. It turned out that the paper tubes made of the new type of paper were 40% stronger than the ones made of recycled paper.

FIGURE 4.68 Paper Dome Theatre – paper tube 10-frequency icosahedron, 2003

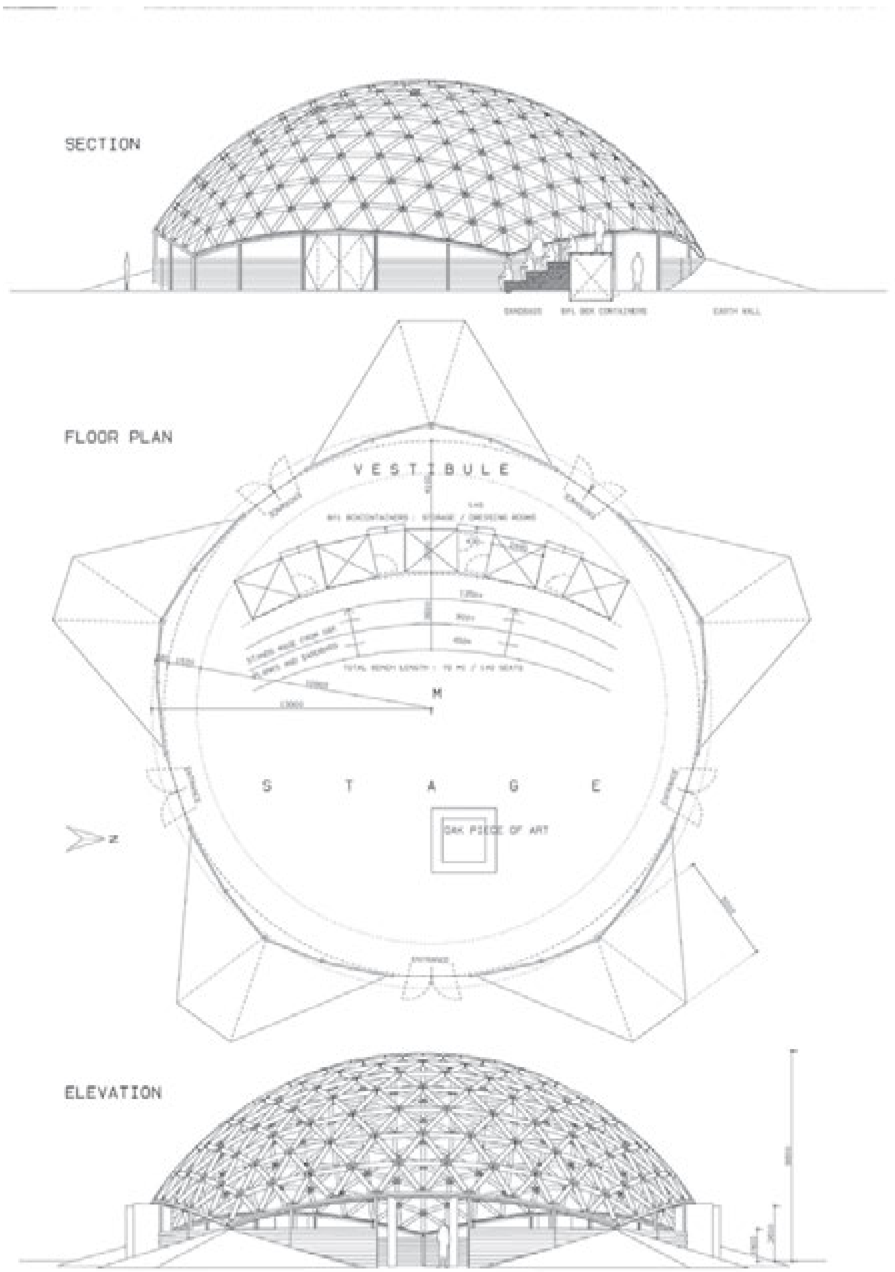

FIGURE 4.69 Paper Dome Theatre – section, floor plan and elevation, 2003

The design conceived by Shigeru Ban was a geodesic 16-frequency icosahedrons dome. However, during the designing process and following discussions with Mick Eekhout, who proposed an 8-frequency dome, Ban changed the design and worked out an idea for a 10-frequency icosahedron dome instead (see Fig. 4.68). This helped increase the length of the paper tubes, produce a smaller number of differently shaped joints and reduce the number of elements used, while preserving the smooth geometry of the dome. The dome had a 26m span and 10m height at the highest point. There were five entrances below curved edge profiles made out of IPE220 steel profiles (see Fig. 4.69).

Five curved edge profiles created the tension ring at the bottom. They were placed on five tetrahedrons to form stable corner columns. The bottom arcs were bolted to the concrete floor slab foundation. As the maximum height of the arcs was 150mm, which would not allow people to enter the dome, it was necessary to dig the ground and lower the entrance level. This problem was solved in the second location (Leidsche Rijn) by placing the foundation elements at the ground level and installing an earth wall all around the building.

The paper tube structure was covered with a PVC-coated polyester fabric membrane. The membrane was attached to small dishes which were placed on threaded rods in the centre of the connection nodes (see Fig. 4.70). Thanks to this solution, a membrane could be stretched and post-stressed by twisting the threaded ends underneath the fabric and pushing the dishes outwards.

Unlike the Japan Pavilion created for Expo 2000 in Hannover, in which long paper tubes crossed each other, the Paper Dome Theatre had a dome whose geometry was defined by joints. Tests proved that cardboard is weak at the transverse screws and bolts. Therefore, a new type of joint had to be created. As the dome was demountable and scheduled to remain in IJburg for a limited period of time, after which it was meant to be transferred to another location, the connections between the paper tubes and joints had to be demountable, as well.

FIGURE 4.70 Paper Dome Theatre – steel joint, 2003

Seventeen different lengths of paper tubes were used for the demountable dome structure. Approximately 700 paper tubes were used with a length ranging from 1,200mm up to 1,500mm. The external diameter of the tubes was 200mm and the walls of the tubes were 20mm thick. The paper tubes were coated with varnish on the outside, on the cutting edges and 100mm inwards to prevent moisture and water from affecting the structure. The paper tubes were held together by means of star-shaped joints made of steel. Each tube was equipped with a steel lid on either end. Both lids were joined by means of a 10mm-threaded steel rod inside the tube. By rotating, the lids compressed the paper tube and converted it into a pre-stressed element (see Fig. 4.71). In the words of Mick Eekhout *this was an essential pre-stressing concept for the cardboard tubes, invented by Luis Weber of Octatube Engineering, which has been used all over the world since then*[24]. This solution meant that no bolt or screw connections were required, and that the compressive strength of the material was used instead. Steel tube collars with an outer diameter of 152mm were welded to the steel lids. They fit into the paper tubes and kept them in position. On the outside of the lids, square steel plates were welded, which were fixed to the star-shaped connector by means of two bolts to acquire a moment stiff node. The steel star-shaped nodes were made of six steel plates welded on a round steel tube.

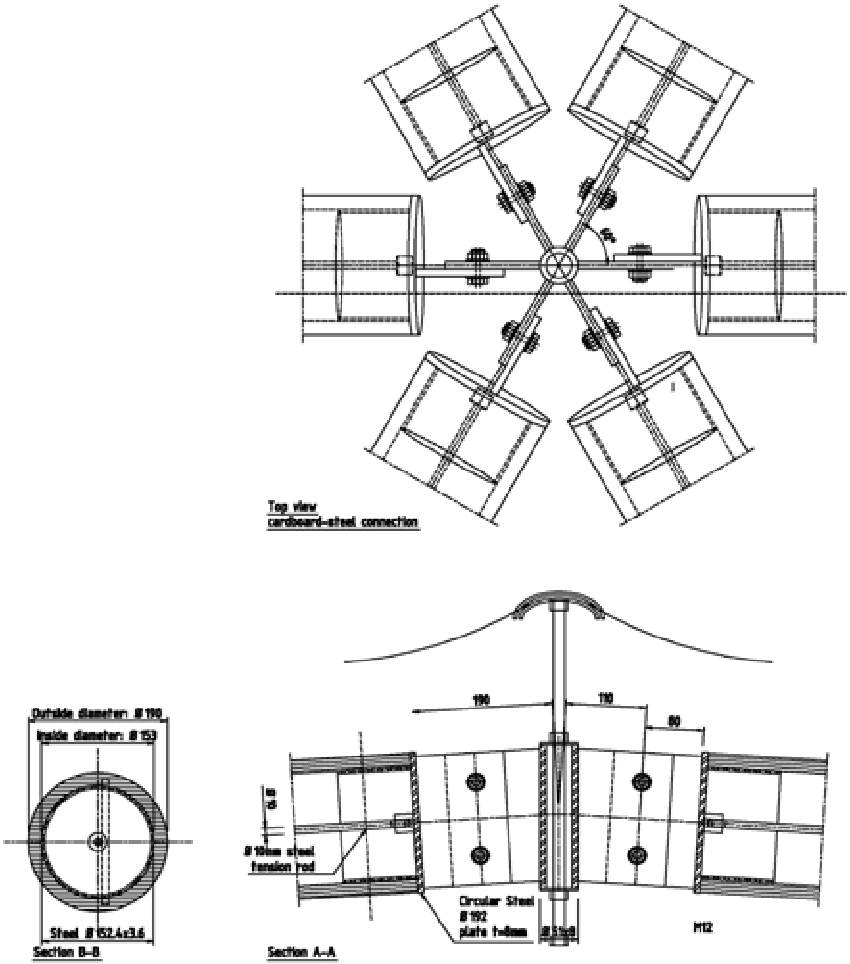

FIGURE 4.71 Nomadic Paper Theatre – steel joint details, 2003

There were eighteen different types of nodes which follow the geometry of the Dome. The types of connections used and the geometry of the Dome resulted in a structure without bending moments in the tubes. All parts of the Nomadic Paper Dome were able to be shipped in four or five shipping containers, which meant the building was truly nomadic. [1, 16, 17, 24]

The Paper Dome has been erected twice and disassembled twice. As of 2017, it is awaiting a new application. For the time being, its components are stored in containers in Amsterdam. Mick Eekhout regrets that due to the short lead-in time of two months for initial engineering and production, no time was available to develop cardboard nodes or composite nodes. He hopes to do so in the future.

§ 4.3.10 Cardboard House, Sydney, Australia

Authors: Peter Stutchbury and Richard Smith, Ian Buchan Fell Housing Research Unit of Sydney University
Year: 2004
Location: Sydney, Australia
Area: 32.4m^2 + 7.9m^2 mezzanine (size: M)
Lifespan: 1.5 years
Type: Housing

In 2004, Australian architects Peter Stutchbury and Richard Smith, in cooperation with the University of Sydney, designed and built the Cardboard House. The project was a part of the Houses of the Future exhibition. Six architectural teams were asked to design a proposition for future housing concepts with ambitious and physical experiments. The houses designed had to be portable and consist of one single material. Six concepts were presented, each made of a different material (concrete, cardboard, glass, clay, steel and timber). Cardboard House was shown to be a low-energy, lightweight, easy-to-transport-and-erect and recyclable solution. As the architects wrote in their submission to the Centre for Affordable Housing, 'The cardboard house represents the reduction of technology, the simplification of needs and the integration of common sense to make a building that may realistically consider a proposal for future living.' [25]

The authors' idea was to create a temporary structure, 85% of which consisted of recycled materials, which could be fully recycled into cardboard after its period of use (see Figs. 4.72 and 4.73).

The building consists of cardboard A-shaped portal frames interlocking with horizontal cardboard spacing beams (see Fig. 4.75). Six portals create five spans of 1.8m each. Simple interlocking pieces result in a rigid and low-technology structure. The house can be expanded in both width and length.

The open space contains service pods like a kitchen and bathroom, with a sleeping mezzanine upstairs, as well as a living-room section on one side (see Fig. 4.74). On the opposite side of the service pods there are pivot door panels, which allow for expanded liveable space. The open space allows cross ventilation and flexible adjustments for the seasonal cycles. Energy is provided by the photovoltaic panels that generate 12 V power.

FIGURE 4.72 Cardboard House, Sydney, Australia, A-frame cardboard structure, 2004

FIGURE 4.73 Cardboard House, Sydney, Australia, connections between the structural elements, 2004

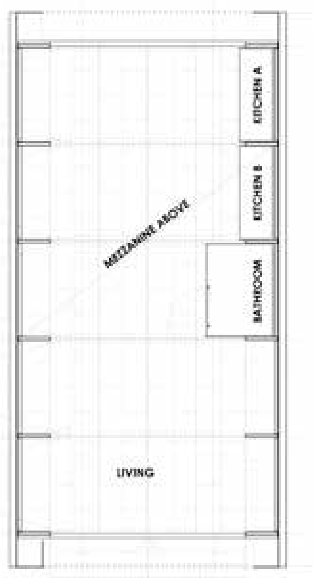

FIGURE 4.74 Cardboard House, Sydney, Australia, floor plan, 2004

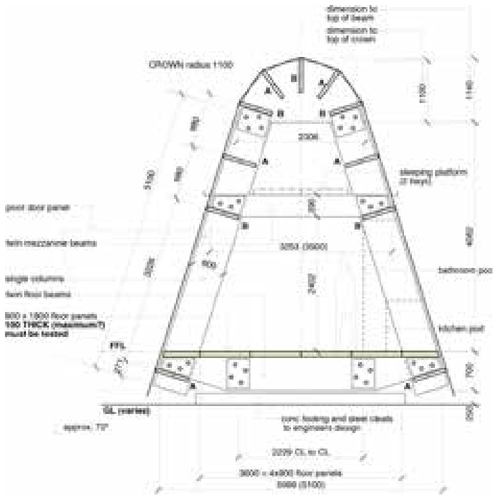

FIGURE 4.75 Cardboard House, Sydney, Australia, section, 2004

The material used in the project was 60mm laminated fibreboard (full cardboard).

Each of the A-shaped frames was composed of two 5,100x600x60mm beams and a semi-circular crown. Nine horizontal spacers (10,200x600x60mm) were interlocked in each of the frames (see Fig. 4.76). The minimised number of fixings between the elements was achieved by interlocking parts of the structure. Elements were held together by 10mm thick cardboard locking plates, 50mm PET tubes and M12 nylon threaded rods.

The outer skin of the Cardboard House was made of HDPE, which also allowed the inhabitants to store grey water in tanks under the floor.

The whole structure was able to be transported by a light commercial vehicle as a flat package, weighing in at 2,000 kg. Most of the members had the following dimensions: 5,000x600x60mm. The Cardboard House was assembled by a group of people who did use scaffolding, but no special equipment. The cost of one kit was approximately AUS$35,000, which equalled €21,500 in 2005. The structure was exposed for approximately a year and a half at three exhibitions held in 2004 and 2005.

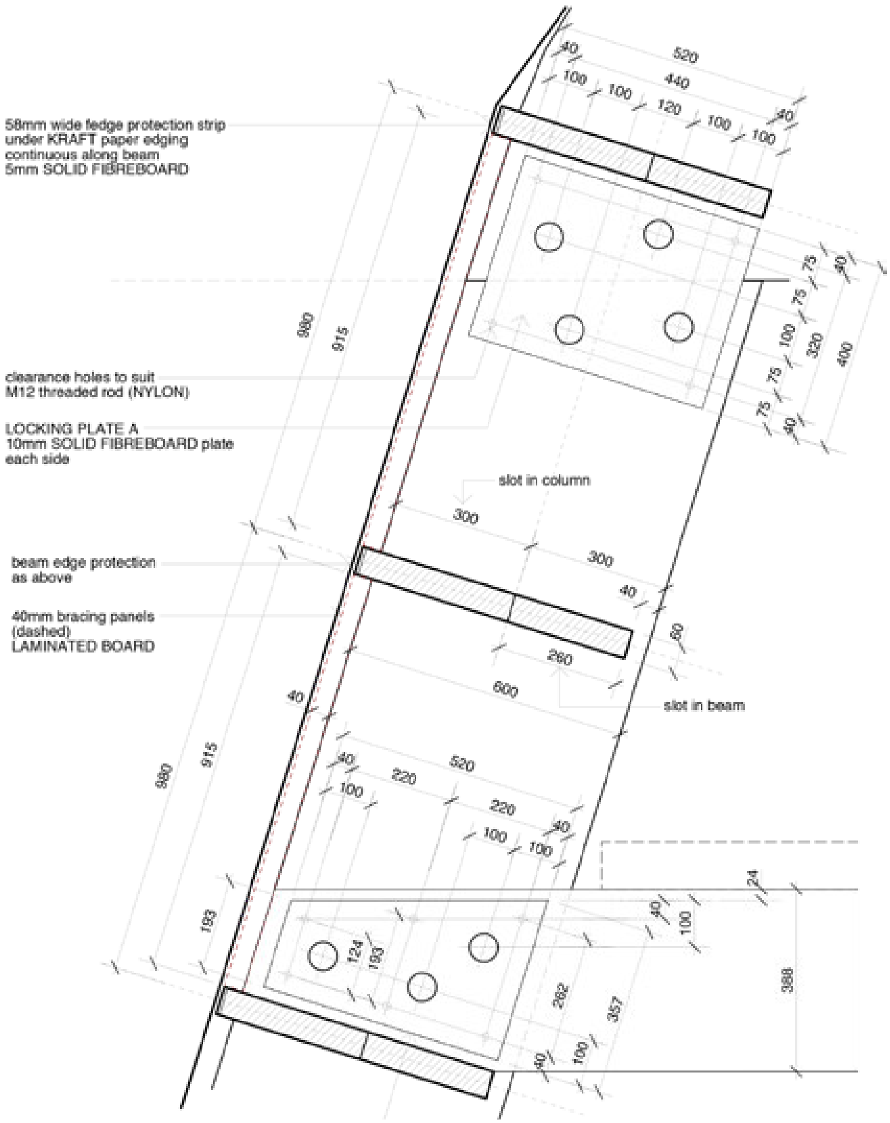

FIGURE 4.76 Cardboard House – detail of the connection between the A-frame and the horizontal spacers, 2004

§ 4.3.11 Hualin Primary School

Authors: Shigeru Ban Architects, Voluntary Architects Network, students of Shigeru Ban Lab and Hironori Matsubara Lab at Keio University, Chengdu Southwest Jiaotong University
Year: 2008
Location: Chengdu, Sichuan Province, China
Area: 3x174m^2 (size: L)
Lifespan: Semi-permanent (estimated five-year lifespan)
Type: Public building/ Emergency

After the major earthquake that shook Chengdu, the capital of Sichuan province, on the 12th of May 2008, Shigeru Ban contacted Professor Hironori Matsubara, who taught at the same university as Ban (Keio University in Tokyo) and also worked as a building consultant in Beijing. A month later, Shigeru Ban, together with volunteers from Ban Lab at Keio University and Chengdu Southwest Jiaotong University, presented a prototype for a house for the victims of the earthquake. At the same time, the Chinese government embarked on a programme designed to build temporary houses for those who had lost their homes due to the earthquake. Although Shigeru Ban was not commissioned to build these houses, he acceded to the request made by the local Rebirth of the Environment NGO and Chengdu Chenghua Primary School that he design and build a temporary Primary school in Chengdu's Hualin district.

Shigeru Ban prepared a proposal for three oblong buildings, each of which contained three classrooms, 9.7x6m per classroom as desired. One of the classrooms was divided into two rooms to provide space for the administrative staff and educators. Each pavilion had an area of 29x6 metres, plus a covered corridor that was 1.5 metres wide (see Fig. 4.77).

The Education Bureau requested that construction be completed by September, to allow students to go to school when the new semester started. While the new school was being designed, the existing and damaged classrooms were demolished. The foundations of the destroyed school were retained and used as the foundations for the newly to be built construction.

The buildings were constructed by students of Tokyo's Keio University and Chengdu's Southwest Jiaotong University as well as volunteer teachers of the school. One hundred and twenty volunteers were divided into three teams, and in order to ensure that the structure was completed before the start of the new school year, a competition was announced for the best and fastest team. All three structures were built in forty days.

FIGURE 4.77 Hualin Primary School, Chengdu, China, 2013

The structural system of Hualin Primary School is based on transverse frames built out of paper tubes. Each of the three erected buildings is 6x29 metres and consists of thirteen transverse frames (see Fig. 4.79. Each frame was constructed out of four paper tubes whose dimensions were 240mm (outer diameter) and 18mm (wall thickness), connected longitudinally with another five paper tubes with the same size (see Fig.4.78). The vertical paper tubes that support the walls are 2,200mm high, the diagonal paper tubes for the roof structure are 3,120mm, and the longitudinal paper beams are 2,200mm long. The paper tubes of the transverse frames are connected with wooden box-shaped joints with studs to which paper tubes are attached. The joints were ordered from a local factory. After they arrived, it appeared that they were empty inside. Some additional reagent had to be used to fill the joints and make them strong enough. Each frame is additionally braced with steel rods. The longitudinal connection between the frames and beams is made of two 18mm laminated plywood boards cut into the shape of a ring with protruding plates to which other plywood plates were fastened to create a cross-like connection. The whole structure was stiffened with plywood boards attached to the paper tube rafters.

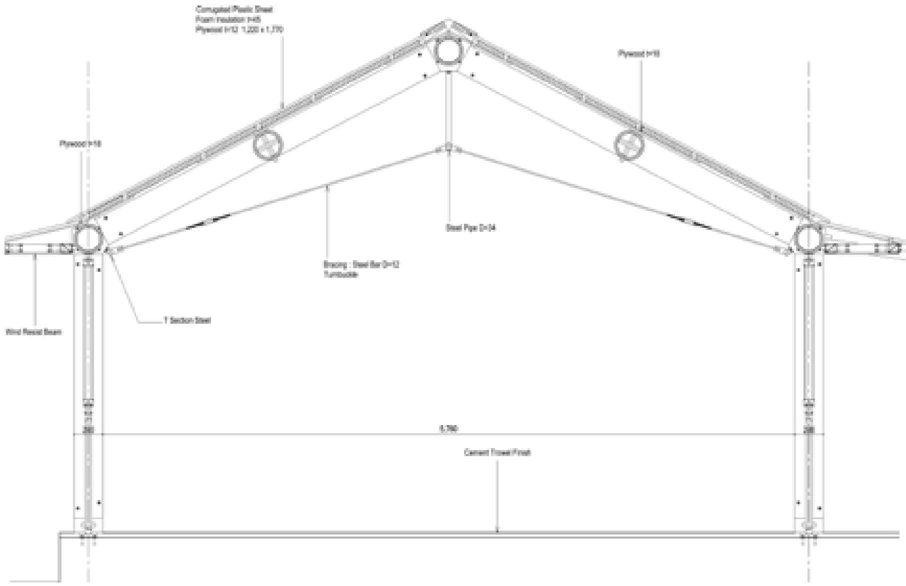

FIGURE 4.78 Section of Hualin Primary School, 2008

The architect's intention was to design a structure which would be easily erected by non-professional construction workers, such as students or volunteers. There are four different types of joints (see Fig. 4.80). The top joints that connect the rafters and columns are designed as wooden blocks with off-standing arms in the shape of octagons to which the paper tubes were attached and fixed in place with 12mm bolts with nuts. The off-standing arms are placed at an angle of 125° for joint A between the rafters and 118° for joint B between the rafter and the column (see Fig. 4.82). The joints for the beams in the middle of the rafter are composed of two 18mm laminated plywood boards. The bottom joint is composed of a rectangular base with an octagonal pin and a T-shaped steel plate at the bottom, which connects the joint to the foundation by means of anchor bolts. The joints were designed in such a way as to facilitate the installation of the frame on the ground and then to connect it with another, previously built frame by raising the whole frame with ropes and manpower. The bolts that fix the paper tubes in position go through the paper tubes and octagonal pins and are tightened from the outside with nuts. Thanks to the octagonal shape of the pins, it was very easy to position the holes for the bolts. The joints are composed of four parts fastened with glue and a steel rod with a diameter of 12mm. They were ordered from the local factory, and as mentioned before, they arrived empty inside. They had to be filled up with an additional extender to ensure they were strong enough.

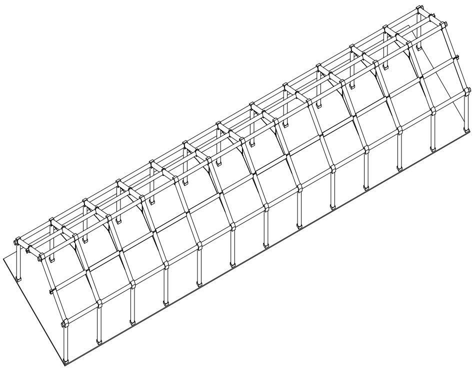

FIGURE 4.79 Axonometric view of Hualin Primary School structure, 2008

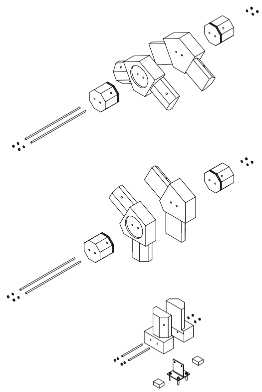

FIGURE 4.80 Hualin Primary School, timber joints types, 2008

The foundations of the previous school building, which was damaged by the earthquake, were re-used for the new Hualin Primary School. The concrete slab was cleaned and prepared during the design process. However, the foundations were too low, and when it rained, water was able to reach the wooden base joint. This resulted in capillary rising damp and its transfer to the paper tubes. The bottom parts of some paper tubes were damaged and had to be replaced with steel tubes as a consequence (see Fig. 4.81).

The walls in the buildings are made out of the PVC sashes with glazing. Panels were fixed to the paper columns through wooden battens screwed to the tubes. Short side walls were built to serve as solid walls, made out of painted white plywood boards with thermal insulation material in between. The wind loads are carried by these solid walls in the cross direction. In the longitudinal direction, wind loads are carried by long paper beams and plywood panels fixed to the paper tube rafters.

FIGURE 4.81 Hualin Primary School – damaged paper tubes, 2013

FIGURE 4.82 Hualin Primary School – 1:1 scale mock-up, timber joint detail, 2013

Hualin Primary School has a clear and simple roof structure. Diagonal paper tubes serve as rafters. They were rendered harder by five rows of paper tube beams and additionally by steel bracing (see Figs. 4.84 and 4.85). Plywood boards were attached on the top of rafters, which makes the structure stronger in the longitudinal direction. The boards have round cuts in the middle in order to reduce their weight. Insulation foam and corrugated plastic sheets were placed on top of the plywood boards. The roof and eaves of the exterior corridors were constructed using timber beams and plywood. [1, 16, 19, 20, 26]

Hualin Primary School was initially built in 2008 for a five-year period. However, the building was still occupied in 2013, after the end of the estimated lifespan. The school's headmaster told the author there were no immediate plans to abandon or dismantle the building. It is important to keep in mind that in certain situations, like emergency situations, the predicted lifespan of a structure can be significantly extended.

FIGURE 4.83 Hualin Primary School – roof structure, 2013

FIGURE 4.84 Hualin Primary School – 1:1 scale mock-up, roof structure, 2013

§ 4.3.12 Ring Pass Field Hockey Club

Authors: Nils Eekhout, Octatube
Year: 2010
Location: Delft, the Netherlands
Area: 128m^2 (size: L)
Lifespan: Permanent
Type: Public building

In 2010, Nils-Jan Eekhout of the Dutch company Octatube designed and built a multi-functional extension of the clubhouse of Ring Pass Field Hockey and Tennis Club in Delft. Octatube had previously cooperated with Shigeru Ban on three projects in which paper tubes were used as a construction material: Demountable Paper Dome (2003), Vasarely Pavilion (2006) and Paper Bridge (2007). Each of those projects was a temporary structure. The non-realised cardboard space frames of TU's Faculty of Architecture were one reason to continue the development of a cardboard space frame system, this time designed and executed by the technical director of Octatube. Nils Eekhout's space frame roof structure, consisting of paper tubes, was a permanent one. The space frame consists of paper tubes connected by recycled steel spheres, i.e., Tuball. The structure was prefabricated on the ground in two parts measuring 8x8 metres each and lifted into position. The roof structure is supported by steel columns (see Figs. 4.85 and 4.87).

FIGURE 4.85 Ring Pass Field Hockey Club, social room, 2012

As with the Nomadic Paper Dome, the paper tubes were not connected by screws so as to avoid concentrated forces which could easily damage the cardboard, but rather by pre-stressed steel threads that were placed inside the tubes and were connected to the Tuball. The threads end in nuts inside the openable Tuball. Tightening them means that the paper tubes are subjected only to stress. The flanges of the Tuballs are sealed with rubber in order to prevent the ingress of moisture (see Figs. 4.86, 4.88, 4.89).

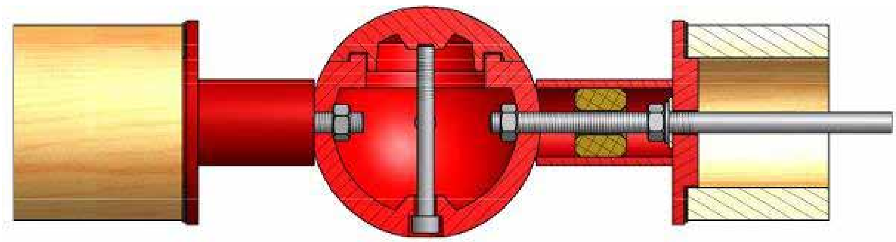

FIGURE 4.86 Ring Pass Field Hockey Club, section drawing of a Tuball, 2010

FIGURE 4.87 Ring Pass Field Hockey Club, social room roof structure, 2012

At the Ring Pass Field Hockey Club, various alternatives were used to protect the paper tubes. The paper tubes are not directly exposed to external weather conditions. The paper tubes were treated against water and moisture in three different ways, which are monitored periodically:

1. Tubes with polyethylene sleeves. The sleeves were applied to the paper tubes, then treated with heat to shrink them. There are two types of sleeves. One covers only paper tubes; the other covers paper tubes and the flanges of the Tuballs;
2. Tubes painted varnished on the inside and outside;
3. Tubes left completely untreated. Humidity does not affect the uncoated paper tubes inside the building.

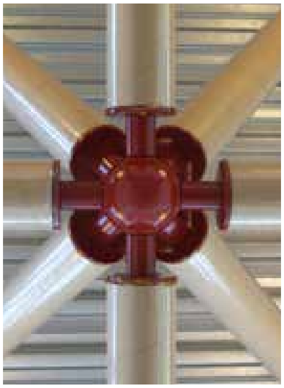

FIGURE 4.88 Ring Pass Field Hockey Club, Tuball – connection between paper tubes, 2012

FIGURE 4.89 Ring Pass Field Hockey Club, Tuball – connection between paper tubes and steel column, 2012

The Ring Pass Hockey Club was authorised to use the paper tube space frame for a permanent structure. It was the first example of a permanent structure made of cardboard in the Netherlands. The building is fully compliant with the requirements for permanent buildings. It is also fully compliant with Dutch fire safety requirements. Contrary to popular belief, cardboard created by high-density material creates a carbon layer when subjected to flames. It takes a long time before this type of cardboard catches fire.

Prior to the Ring Pass Field Hockey Club, Prof. Mick Eekhout designed a cardboard space frame for TU Delft's Faculty of Architecture's Glass Houses. As the project was never realised, a description of it is provided below, rather than in a separate sub-chapter.

Cardboard space frame for TU Delft's Faculty of Architecture's Glass Houses

Authors: Mick Eekhout, Octatube Nederland B.V.
Year: 2008
Location: Delft, the Netherlands
Area:30x50m / 30x30m (size: XL)
Lifespan: Initially estimated to be five years, but later defined as permanent
Type: Public building

This Demountable paper dome, designed in 2002, was based on Octatube's nodal space frame system. In 1984 the Octatube company had developed a more abstract system, with hidden bolts and tubular bars and spherical nodes, known as the Tuball system. It was originally executed in aluminium, but mostly in steel. The biggest span realised was 80x150m for a Boeing 747 maintenance hall in Mumbai. In the original design for the extension to the existing TU Delft main office building, to be used by the Faculty of Architecture, it was decided that two large glazed halls should be added, an east-facing hall (30x30m) and a south-facing hall (30x50m) (see Fig. 4.90).

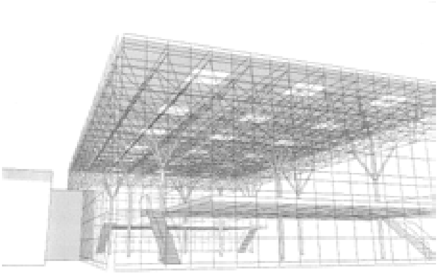

FIGURE 4.90 Axonometric view of the east-facing hall (Orange Hall), 2008

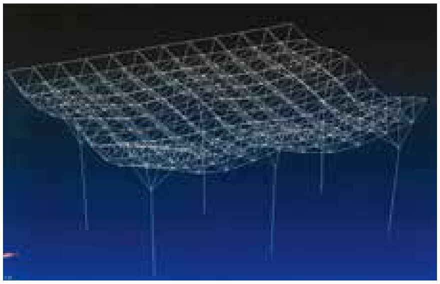

FIGURE 4.91 Static analysis schemed loaded with exaggerated deformations of the card board space frame of the south-facing hall, 2008

In October 2008 a contract was signed stating that both halls would be built using cardboard space frames. As the spans created by cardboard frames are limited in size, it was decided that the spans of the hall would consist of five modules of 1,350m. As a result, both halls have intermediate columns inside the space of the hall. A steel space frame could do it with a free span (see Fig. 4.91). The cardboard mechanical properties were calculated by Octatube on the basis of the data collected in 2002 for the Paper Dome project. The planning of rebuilding after the great fire of the Faculty of Architecture in May 2008 was tremendous and tight. It included three months of experimentation to develop a reliable and certified treatment for the cardboard tubes, so that they would have a long lifetime – twenty to thirty years. One month after the signing of the contract, TU Delft decided that the first hall had to be finished before the start of the 2009-2010 academic year. This meant that by Octatube's three months of experimentation and research had been in vain. Concrete piles, 25m long, had already been driven into the ground, so the underground situation could no longer be changed. The column supports stayed in the same position, and instead of a cardboard space frame, a standard steel Tuball space frame was realised, and the building was scheduled to be completed just in time for the start of the new academic year (see Figs. 4.92 and 4.93). In 2010, Ring Pass hall succeeded the TU Delft cardboard space frame.

FIGURE 4.92 Realised steel space frame for the south-facing hall Faculty of Architecture TU Delft, 2017

FIGURE 4.93 Space frame structure of the south-facing hall, Faculty of Architecture TU Delft, 2017

§ 4.3.13 Shigeru Ban Studio at Kyoto University of Art and Design

Authors: Shigeru Ban Architects, students of KUAD
Year: 2013
Location: Kyoto, Japan
Area: 142m^2 (size: L)
Lifespan: Temporary
Type: Public building

n 2013 Shigeru Ban became a professor at Kyoto University of Art and Design. To host the students, Ban designed and built a structure similar to the Paper Dome with his students. The arched surface had previously been used as a studio for Ban Lab at Keio University in Fujisawa, Kanagawa Prefecture, in 2003. In addition, it had been used as Shigeru Ban Architects' temporary studio on the sixth-floor roof terrace of Centre Pompidou in Paris in 2004.

The studio covers a usable area of 11.7x12.1m^2. The gable walls were made out of wooden frames covered with PVC-corrugated panels (see Fig.4.94).

FIGURE 4.94 Shigeru Ban Studio at KUAD, front wall, 2013

Unlike his three previous arch structures, this time Ban used steel joints in order to be able to re-use the structure after its disassembly. The structure of a single arc is composed of six paper tubes with an internal diameter of 170mm. The walls of the tubes are 3.5mm thick and the tubes are 1,860mm long. Twelve arcs are connected with five rows of horizontally placed paper tubes with a length of 850mm and the same diameter (see Fig.4.96). The paper tubes were not connected to the steel joints by means of screws or bolts, as was the case in the previous arc structure. This time, as with the Library of a poet, the Dutch Paper Dome and Ring Pass Hockey Club, the steel threads which were placed inside the tubes tightened the tubes, causing axial compression. Ban now used two tensile rods rather than one (see Fig. 4.95). This called for further development of the end fitting of the cardboard tube.

Transverse tubes were connected and screwed to wooden pegs. The wooden pegs were inserted into the hollow steel connectors of the arches (see Fig. 4.98). Metal joints were connected with bracing in order to keep the structure rigid and to prevent changes in the load distribution due to snowfall (see Fig. 4.97). The surface created by the paper tubes was covered with structural plywood panels. Each of the panels with round openings of 750mm was attached to battens, which were screwed to the paper tubes from above.

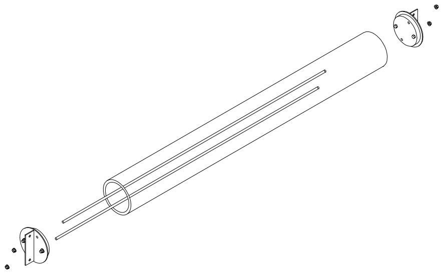

FIGURE 4.95 Shigeru Ban Studio at KUAD, post-stressed connection between paper tube and steel joint with two threads, 2013

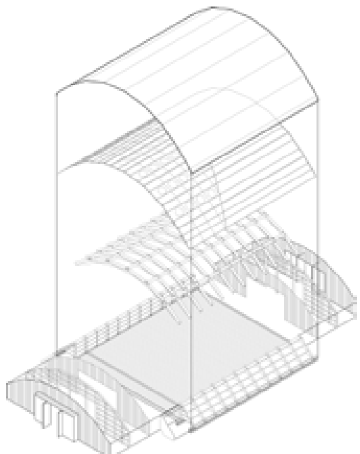

FIGURE 4.96 Shigeru Ban Studio at KUAD, exploded axonometric view, 2013

The structure was placed on top of the concrete slab that covered a big university hall underneath. On the slab, a concrete foot carried 250x250mm steel H beams on either side of the arcs. The corners of the arcs were strengthened by timber boxes that served as shelves.

FIGURE 4.97 Shigeru Ban Studio at KUAD, view from the inside, 2013

FIGURE 4.98 Shigeru Ban Studio at KUAD, detail of a paper-tube connector, 2013

§ 4.3.14 Miao Miao Paper Nursery School

Authors: Shigeru Ban Architects, VAN; structural engineer: Minori Tezuka; construction: students of Shigeru Ban Studio, Kyoto University of Art and Design and Southwest Jiaotong University
Year: 2014
Location: Taiping Town, Ya'an City, Sichuan, China
Area: 117.6m^2 (size: L)
Lifespan: Semi-permanent (estimated lifespan five years)
Type: Public building/ Emergency

On 20 April 2013, a huge earthquake shook China's Sichuan province. It had a magnitude of 7 on the Richter scale. Shigeru Ban, who had built the temporary paper structure of Hualin Primary School in Chengdu after another earthquake in Sichuan five years previously, went to China to see if his structure had survived the earthquake. The Hualin School, built in 2008, had escaped unscathed. During the trip, Shigeru Ban visited the small town of Taiping near Ya'an city. About 70% of the town had been destroyed by the earthquake. Shigeru Ban decided to design and build a kindergarten for the youngest citizens of the town. The architect invited students from the Shigeru Ban Studio at Kyoto University of Art and Design, including the author of this thesis, who was in Kyoto at the time to conduct research on the use of paper as an architectural material. The design team consisted of the architect Yasunori Harano, an assistant of Ban's at Shigeru Ban Architects and KUAD University; the architect Mirian Vacari, a Brazilian architect interested in paper architecture; the architect Jerzy Latka and three students: Alexander Riva, Yuta Sakurai and Hoshi Kazufum.

The designers' intention was to erect a semi-permanent building that would last 5-7 years, built on a plan of a 3x3m grid. The building was to be 21 metres long and 6 metres wide (see Fig. 4.99). The building was divided into two classrooms with an interior corridor and the main entrance in between. Initially, the idea was to have columns delineating the 3-metre grid, but later the school teacher decided that columns in the middle of the classrooms would interfere with the conduct of the children's activities. So the columns in the middle were removed from the design and the structure was re-calculated in order to obtain structural stability (see Fig. 4.100).

FIGURE 4.99 Miao Miao Paper Nursery School, 2014

Before the design was finished, a 1:1 scale mock-up of the connection between the wooden joints and the paper tubes was made (see Fig. 4.101). The mock-up would demonstrate whether it would be possible to reach the bolts with the appropriate tools.

The design process was completed in September 2013. The author, who had already returned to Poland by this stage, received an invitation to the building site in Chengdu and went there in November to help out for a month. Some fifteen volunteers were already involved in the project, divided into two groups. One group went to Taiping, while the other stayed in Chengdu. The first few weeks were devoted to work on the foundations of the building site, the impregnation of paper tubes and the preparation of wooden joints at Liu Yang Architect workshop in Chengdu.

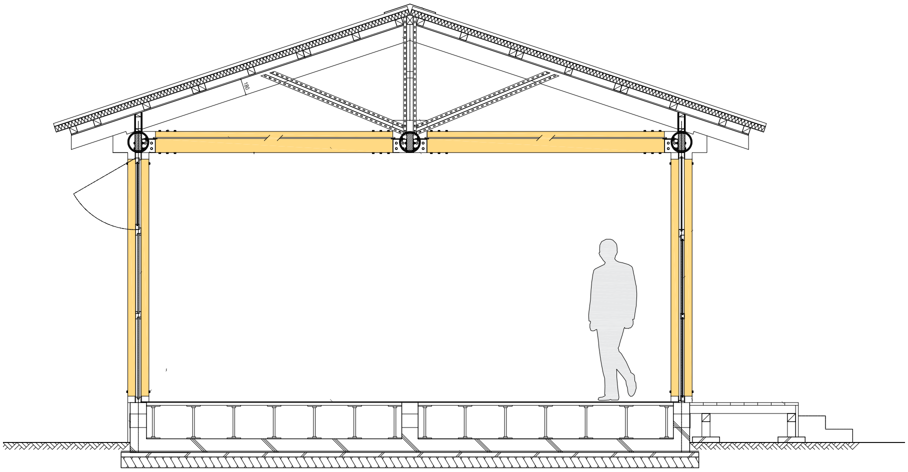

FIGURE 4.100 Miao Miao Paper Nursery School, detailed section, 2013

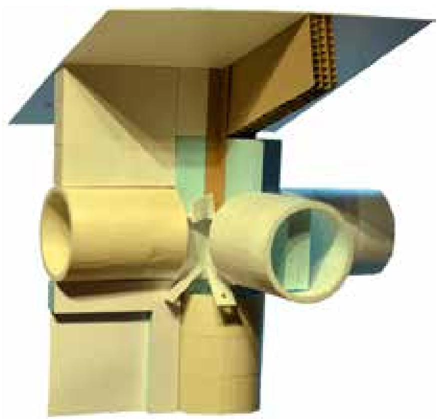

FIGURE 4.101 Miao Miao Paper Nursery School, 1:1 mock-up of the paper-tube connection, 2013

FIGURE 4.102 Miao Miao Paper Nursery School, preparation of wooden joints in Chengdu, 2013

The wooden joints were created by the second group of volunteers, including the author (see Fig.102). After two weeks' preparation, during which all the wooden elements had been prefabricated and all the necessary components like insulating foam, roof cladding, perforated L-angles etc. had been bought, the volunteers went to Taiping. After they had levelled the base joints (joint A), the erection of the paper tube structure commenced (see Fig. 4.104). Paper tubes had been impregnated in advance by dipping them into polyurethane liquid. The erection of the structure itself was to be a very fast and easy process, especially as the project was designed in such a way as not to use any crane. Unfortunately, some new problems arose, which delayed the construction process. For instance, the steel elements were the wrong colour, and the bracing elements had been threaded incorrectly. After two weeks at the site, the paper tube structure was completed. The next few weeks were devoted to the roof structure, the installation of the wall panels, the interiors and landscaping. The building was opened to the public on 1 April 2014.

FIGURE 4.103 Miao Miao Paper Nursery School, construction of the paper tube structure, 2013

Ya'an Nursery School's structural system consists of paper tubes serving as columns and beams (see Fig. 4.104). The roof structure is a mix of timber and steel perforated L-angles. The paper tube structure was built out of 49 paper tubes with a length of 2,617mm each. The outer diameter of the tubes was 234mm, while the walls of the tubes were 15mm thick. The whole structure was strengthened with horizontal and vertical bracing rods. The bracing brought extra stability in case another earthquake would strike. As paper tubes are flexible and able to hold the lateral and vertical forces caused by an earthquake, other elements made of timber or plastic might break. Steel bracing held the flexible structure of paper tube beams and columns in place. The new structural solution Shigeru Ban wanted to apply in Ya'an Nursery School was dictated by the problems the architect had faced during the construction of Hualin Primary School in Chengdu in 2008. To prevent running the same risk, Ban had proposed cross-like wooden joints made out of laminated timber boards.

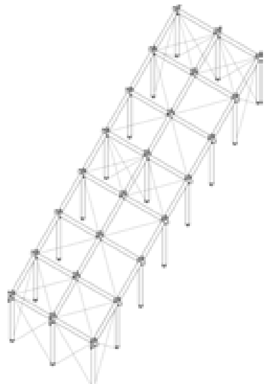

FIGURE 4.104 Miao Miao Paper Nursery School, axonometric view of the structure, 2013

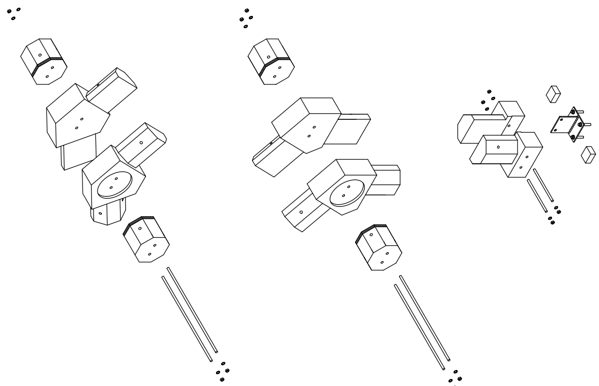

FIGURE 4.105 Miao Miao Paper Nursery School, wooden joints between paper tubes, types: a), b), c) and d), 2013

A new solutions for wooden joints was used in the project. This time the joints were to be prepared by the volunteers at a local workshop. Therefore, they had to be easy to manufacture. Four types of wooden joints were used (see Fig. 4.105). Bottom joint A was used at the base of the columns; top joint B was used to connect the columns, beams and wooden roof structure, located at the side of the building; joints C and D were used to connect the paper tube beams and the steel roof structure in the middle. Joints C and D are different only in that they have a pin for the columns; joint C hangs, while joint D lies on top of the columns. Joints B, C and D are composed of two flat elements which, when inserted into each other, look like a cross with four arms, each at an angle of 90° when viewed from above. Joints are made out of laminated timber with the thickness of 72mm. This type of joints allowed a significant reduction in the weight which resulted in the possibility of connecting joints and tubes in the air (see Fig. 4.107). The joints were fixed together with L-shaped steel plates that were used as a place to attach horizontal and vertical steel bracing. Although the joints required less material and were lighter and easier to produce, they made the entire structure much more complicated, because of the additional steel plates and bracing required.

FIGURE 4.106 Foundations of Miao Miao Paper Nursery School, 2013

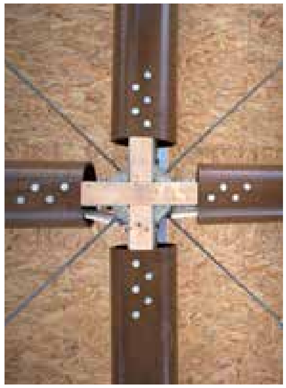

FIGURE 4.107 Wooden joint, type C, 2014

Ya'an Nursery School's foundations were raised up to 440mm from the ground level to prevent the paper tubes from being damaged by water (see Fig. 4.106). This was a lesson learned during Shigeru Ban's previous construction project in the region, Hualin Primary School. Due to the raised foundation, it was possible to create openings in the foundation wall and provide UFAD (Under Floor Air Distribution) so as to lower the temperature inside the classrooms. Steel plates installed beneath wooden joint A keep the bracing rods in place to ensure the building's stability.

The building's walls were made out of PVC sashes with glazing. Panels were fixed to the paper columns through wooden battens screwed to the tubes. The wall was rendered rigid by means of horizontal and vertical bracing, which is present in all spans of the building. Vertical bracings abutted the internal side of the walls.

The roof structure was the most complicated part of the building. It is a mix of wooden beams and perforated L-angles (see Fig. 4.108). The angles had been used in a previous Shigeru Ban project, Atelier for a Glass Artist, built in Tokyo in 2006. The wooden rafters are connected to joint C or D by means of perforated L-angles measuring 35x35mm and 3mm thick. The L-angles are arranged in pairs on either side of the joints. The horizontal bracing rods also pass through the joints. An OSB board layer (oriented standard board or flakeboard) lies on the rafters, with a purling and thermal insulation foam in between. The roof is covered with a layer of steel plates. Large eaves should protect the paper tubes from getting wet due to rain. [20, 26]

FIGURE 4.108 Paper tube, timber, perforated L-shape and steel bracing composition of the roof structure, 2014

§ 4.3.15 Wikkel House

Authors: René Snel (invention), further developed by Fiction Factory
Year: 1996 (invention), further development: 2012-ongoing
Location: no fixed location
Area: 5m^2 per segment (size: M)
Lifespan: fifty years (with fifteen years' warranty)
Type: Housing

In the late 1990s the Dutch inventor René Snel created the concept for a house composed of several layers of single-face corrugated cardboard. He was inspired to create Wikkel House (wikkel is the Dutch word for 'wrapper') by cardboard transportation crates for tomatoes, which were produced by wrapping corrugated cardboard around a mould and laminating it. Snel created the machine which wrapped segments of the house. Wikkel House was first and foremost designed as a temporary housing solution for areas struck by disaster. Therefore, the machine producing the 'wraps' was attached to the back of the truck, so as to be mobile. By transporting the machine and rolls of corrugated cardboard to disaster-stricken areas, crews would be able to manufacture houses on site. However, none of the non-governmental organisations involved in emergency relief was interested in launching the project, so it was aborted in 2008. A few years later, an Amsterdam-based company called Fiction Factory bought the machine and the intellectual property of Wikkel House and commenced development of the project (see Fig. 4.109). The first house produced by Fiction Factory was exposed to the public at Amsterdam Schiphol Airport in 2012.

FIGURE 4.109 Wikkel House showroom at Fiction Factory, Amsterdam, 2016

Wikkel House consists of prefabricated segments, each 4.6m long and 3.5m high. Each segment is 1.2m wide, in accordance with regular corrugated cardboard production size standards (see Fig. 4.110). Each segment covers a usable area of $5m^2$. The segments are manufactured by wrapping and laminating 24 layers of corrugated cardboard, kept in place by wooden frames. The frames serve as the key structural element. Rolled-up corrugated cardboard passes through several rollers that guide it to a conveyor belt, where it is covered in glue. By moving back and forth, the conveyor belt adjusts the tension of the roll, in accordance with the uneven shape of the house.

A braking system determines how tightly the paper is wrapped around the mould. The first layer of cardboard is attached to the two wooden frames. Once 24 layers have been wrapped around the mould, the mould folds inwards and the segment can be taken off the mould. As the lamination process has not yet been completed, and the glue has not yet completely dried, the timber frames act as a mould until the glue has dried completely and the cardboard core has set (see Fig. 4.111).

Next, the segments are covered from the outside with watertight and breathable textile and clad with timber planks, which are screwed to wooden side frames (see Fig. 4.112). On the inside, the corrugated cardboard is covered with plywood. One segment weighs approx. 500 kg. The segments can be transported by flatbed trailer, although only two segments can be transported at a time.

The first example of Wikkel House to be produced was installed at Amsterdam Schiphol Airport. It was covered by an aluminium layer. This was a costly and hard-to-produce solution, so the aluminium was replaced with wooden cladding.

FIGURE 4.110 Wikkel House segments taken off the mould at Fiction Factory, Amsterdam, 2016

FIGURE 4.111 Timber frame and connection with the corrugated cardboard of Wikkel House, 2016

FIGURE 4.112 Timber frame connection and sealing detail of Wikkel House, 2016

FIGURE 4.113 Mock-up of the wall of Wikkel House (section), 2016

FIGURE 4.114 Foundation beam of Wikkel house, 2016

The segments are joined by steel threads that go through the walls and through slots in the wooden frames (see Fig. 4.113). The slots are also used as an exhaust for the moisture resulting from drying glue. Furthermore, the surface is sealed where the various segments connect. Several segments are placed on wooden or steel beams, which are connected to a concrete foot (see Fig. 4.114). The front and back façades are made of timber and glass and attached to the timber frames. One full segment is estimated to take one day to produce.

Wikkel House is advertised as an eco-friendly, comfortable, prefabricated summer house that can be installed at any chosen location within one day. It can be fully furnished and equipped with a toilet, kitchen unit and air conditioning system.

The price for a three-segment Wikkel House starts from €25,000. The expected lifespan of the house, according to the information provided by the manufacturer, is fifty years. However, the warranty period is fifteen years, even if in the Netherlands the legal warranty for products of a structural nature is limited by law to ten years.

In Wikkel House the laminated layers of single-face corrugated cardboard serve as the main structural element. The main structure is founded on 24 layers of laminated corrugated cardboard, which serves as the house's floor, walls and roof, all in one. The wooden frame is mainly used to keep the cardboard in place during the production process, as a connecting element and as fail-safe system in case the cardboard core is damaged.

Several interesting tests were conducted while Wikkel House was developed as a graduation project by Casper van der Meer of TU Delft's Faculty of Industrial Design. [27] One of the issues Van der Meer encountered while doing his research for his Master's dissertation was the drying of glue after a segment of Wikkel House had been produced on the mould and taken off the mould. As long as the PVAC glue had not dried, the cardboard core which is the main structural element of Wikkel House would not achieve optimal strength. Therefore, it was necessary to dry the glue in different places after the wrapping process. Three specimens were tested in order to investigate the drying behaviour of the laminated cardboard, which was covered by a membrane foil that was waterproof but moisture-permeable. One sample was left completely exposed, the second was completely sealed off by means of plastic foil, and the third was wrapped in membrane foil. After one week the relative weight of the moisture content had evaporated by 8% in the exposed sample, by 8% in the membrane-covered sample, and by 0% from the sealed-off sample. The test indicated that more moisture evaporated than was actually applied in the form of glue during the lamination process, which meant that the relative humidity of the cardboard itself was higher than expected. Covering the cardboard core with a waterproof but breathable membrane seemed to be the most desirable solution.

Another interesting test Van der Meer carried out was related to the bending of the material. Two different cardboard sandwiches were prepared. One was made out of recycled cardboard, the other out of virgin cardboard. The samples were as long as the span of the floor of Wikkel House between two foundation beams, i.e., 1.6m. The width of the samples was 0.4m. The test was first performed 24 hours after gluing. The results showed that even if the glue was not yet dry completely, the sample composed of virgin cardboard could hold 2.3 times more weight (127 kg) than the one made of recycled cardboard (55 kg). The second test was performed one week after the samples had been glued. This time the virgin cardboard could hold 240 kg, well over twice as much as the recycled cardboard (112 kg) and nearly twice as much as the virgin cardboard sample that had not yet fully dried after 24 hours.

The test results indicate the importance of allowing the glue to dry completely before applying full forces to the structure (before transportation, installation on site, furnishing and use). They also indicate that the strength of the house is strongly dependent on the type of cardboard used (virgin or recycled).

§ 4.3.16 Wroclaw University of Science and Technology 70th Anniversary Pavilion

Authors: Jerzy Latka, in cooperation with students from Wroclaw University of Science and Technology
Year: 2015
Location: Wroclaw, Poland
Area: 70.7m^2 (size: L)
Lifespan: six weeks
Type: Temporary event venue/ exhibition

In the spring of 2014, the author of this dissertation was commissioned by the authorities of Wroclaw University of Science and Technology to design and build a pavilion to mark the occasion of the University's 70th anniversary.

The requirements for the pavilion were as follows. It had to be a structure that would be installed in Solny Square in Wroclaw's city centre, adjacent to the Main Square. It would remain there for about two weeks before being transported to the WUST campus, where it would remain for a few more weeks. The pavilion would be used to present WUST's 70-year history (1945-2015). In addition, the pavilion had to be visually attractive – an eye-catcher that would encourage visitors to learn more about the history and development of the University.

Due to transportation capabilities and the amount of time needed for the construction of the pavilion at Solny Square, the decision was made to prepare the pavilion in the form of components, which could be transported and assembled on site. The size of each component had to be kept under 2.5m (width), 6m (length) and 4.5m (height) to allow transportation to the city centre by a regular-sized truck.

The commission was the perfect occasion to apply cardboard to a large-scale structure. Therefore, the author designed three proposals for a pavilion, each of which involved the use of paper tubes as a primary or secondary structural material.

Modular Pavilion

The author's first proposal centred on the creation of four hexagonal-in-plan modules, which could be assembled after being transported to the square. The pavilion would have six entrances, allowing people to enter from the most popular directions of the people flow at the square (see Figs. 4.115 and 4.116).

Each of the modules was composed of 15 frames made out of paper tubes connected by wooden joints (see Fig. 4.117). The space created by the frames would be used for an exposition of posters hung up on the walls. Since the exhibition could be experienced in a non-linear way, a special scenario would have to be created for the exhibition. Semi-circular spaces outside the pavilion would be used for a further presentation of the University's achievements in the form of mock-ups or additional posters.

The pavilion would be transported in form of curved wall components, connected at the top and bottom by wooden beams. Then the wall components would be connected by means of horizontal paper tubes, thus creating the modules.

The maximum height of the pavilion would be 2.65m (see Fig. 4.118). Five different types of paper tube frames would be involved, with different widths but the same heights. The triangles, created at the centre of the modules, would be covered with a translucent PVC membrane (see Fig. 4.119). A total of 171 paper tubes would be incorporated into the structure, whose external size would be 11x13m.

FIGURE 4.115 WUST Pavilion, version 01, site plan, Jerzy Latka archi-tektura.eu, 2014

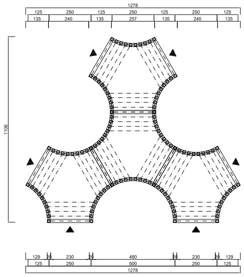

FIGURE 4.116 WUST Pavilion, version 1, plan view of the whole pavilion, 2014

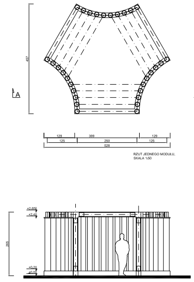

FIGURE 4.117 WUST Pavilion, version 1, plan view and section of single segment, 2014

FIGURE 4.118 WUST Pavilion, version 1, visualisation from the outside, 2014

FIGURE 4.119 WUST Pavilion, version 1, visualisation from the inside, 2014

Social Pavilion

The author's second idea for a pavilion centred on a long and narrow curved corridor composed of paper tube frames. The pavilion would be positioned in such a way as to ensure its entrances faced the main flow of people walking from the Main Square to Solny Square (see Fig. 4.120). The exhibition would be experienced in a linear way. A semi-circular patio covered with delivered grass in rolls would create a social space equipped with cardboard furniture, lending the city centre some added grandeur (see Fig. 4.121). The combination of four modules would result in the pavilion being question-mark-shaped. Each module was in plane a part of a pentagon with circle cut out in the middle. There were 65 frames, composed of paper tubes and wooden joints, with nine different heights (see Fig. 4.122). The pavilion would be 2.20m at its lowest points and 2.80m at its highest point. Prefabricated wall components in the form of paper tubes connected at the bottom with wooden foundations and at the top with wooden beams would be transported and assembled at the Square (see Figs. 4.123 and 4.124). The overall external dimensions of the pavilion were 16x9.3m.

FIGURE 4.120 WUST Pavilion, version 02, site plan, Jerzy Latka archi-tektura.eu, 2014

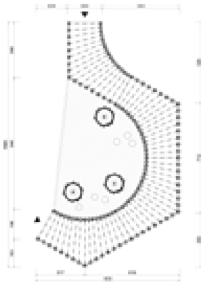

FIGURE 4.121 WUST Pavilion, version 2, plan view of the whole pavilion, 2014

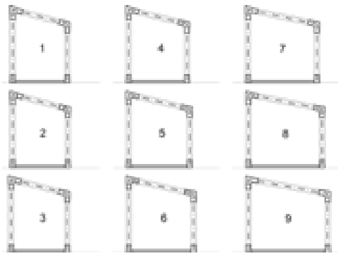

FIGURE 4.122 WUST Pavilion, version 2, different paper tube frames, 2014

FIGURE 4.123 WUST Pavilion, version 2, visualisation view from Main Square, 2014

FIGURE 4.124 WUST Pavilion, version 2, visualisation – view from inside, 2014

Interactive pavilion

The third concept was different from the previous ones in both shape and structure. In this proposal the main structure was composed of wooden arches and paper tubes attached perpendicular to the centre of the arches (see Figs. 4.125, 4.126 and 4.127). The design involved a total of 498 paper tubes, each illuminated by a LED strip with full RGB colours. The paper tubes were 600mm long and had a diameter of 275mm. Their walls were 10.5mm thick. The paper tubes were sealed at the top and bottom by circular Plexiglas plates. Eighty of the tubes were used to hang exhibition boards from. Information about the University was printed on Plexiglas boards attached to the lower half of the tubes.

The exhibition was organised in two linear arrangements on either side of the pavilion. One side of the pavilion showed the development of the University, while the other side showed important moments in its history. The boards placed closer to the floor were designed for children, while the ones placed at a higher level were intended for adults.

The pavilion consisted of six components in the form of semi-circular tunnels (see Figs. 4.142 and 4.143). Each of the components was composed of six laminated timber arches with a radius of 2,350 to 2,650mm (see Fig. 4.128). Different-sized arches allowed the architect to achieve a curved surface of the lit skin made out of paper tubes (see Figs. 4.129, 4.130). The components were small enough to be transported to the city centre by low-bench truck (see Fig. 4.142). After assembly, the size of the pavilion was 11,5x6,15m (see Fig. 4.125).

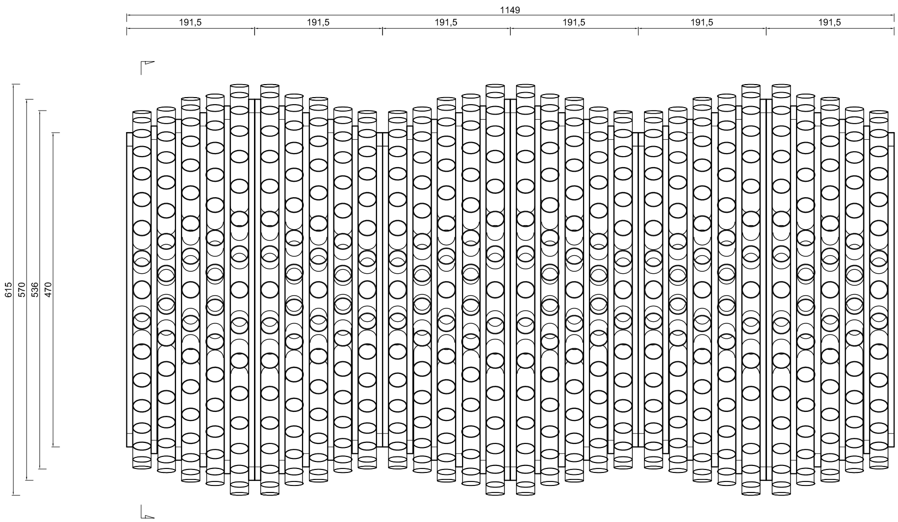

FIGURE 4.125 WUST Pavilion, version 3, plan of the pavilion, 2014

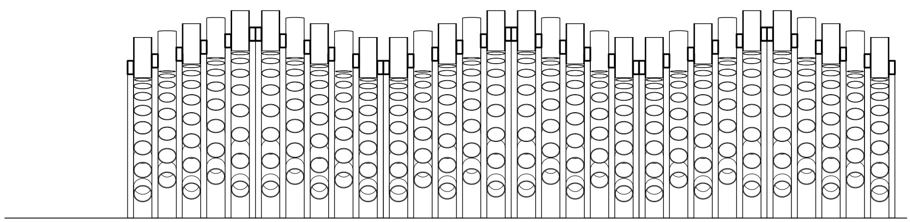

FIGURE 4.126 WUST Pavilion, version 3, section of the pavilion, 2014

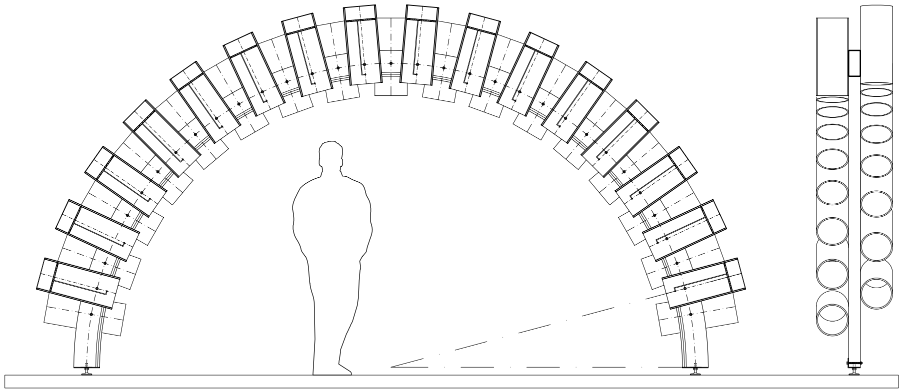

FIGURE 4.127 WUST Pavilion, version 3, detailed section, 2014

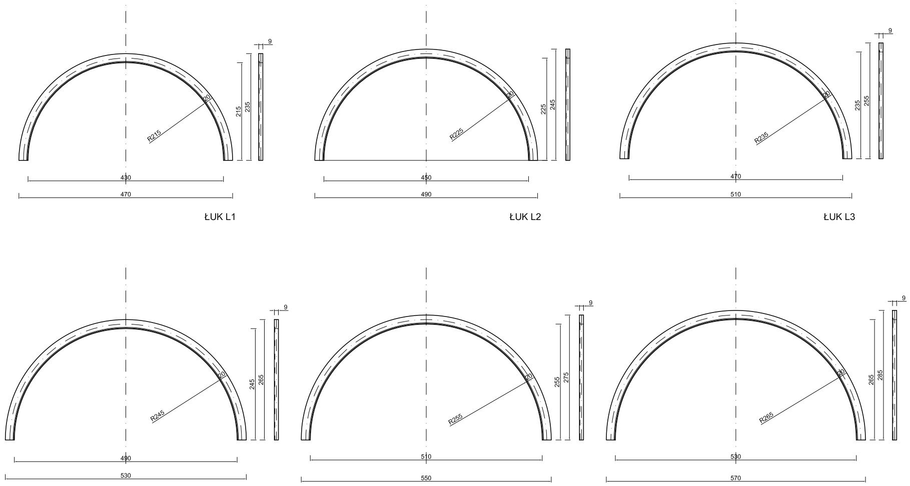

FIGURE 4.128 WUST Pavilion, version 3, different-sized arches for pavilion construction, 2014

FIGURE 4.129 WUST Pavilion, version 3, model of the pavilion, 2014

FIGURE 4.130 WUST Pavilion, version 3, model of the pavilion - entrance, 2014

It was the third idea that was selected for execution. Therefore, it was necessary to create a team consisting of specialists representing different specialities in order to proceed with the construction, electronic equipment installation, exhibition and dynamic illumination of the pavilion.

Four scientific organisations for students attending Wroclaw University of Science and Technology were invited to cooperate. They were the following organisations:

The Humanisation of the Urban Environment organisation affiliated with the Faculty of Architecture. The students making up this organisation were responsible for the general execution of the pavilion and for the exhibition scenario. The exhibition group was led by Monika Pietrosian and consisted of Marta Jastrzebska, Dorota Reclawowicz, Anna Kwapien, Anna Mlodzianowska, Jarosław Kuziemko, Aga Folaron and Bartosz Kołodziejczuk. The members of the general contractor group were led by the author of the pavilion. This group consisted of Katarzyna Dominiak, Karolina Dyjach, Anna Pastor, Emilia Karwowska, Adrianna Kazmierczak, Patrycja Jedra, Marta Gruca, Malgorzata Radaj, Marta Wroblewska, Maciej Marszal, Marta Mochniak, Justyna Romanowska, Krzysztof Gorczakowski and Agnieszka Ejsymont.

The EtaKsi science organisation, affiliated with the Faculty of Civil Engineering, was responsible for the structural stability and transportation of the pavilion. This team was led by Anna Gorska and the group consisted of Adrian Jakubowski, Malgorzata Soroko, Adam Sterniuk, Agnieszka Helik, Justyna Kiedrzyn, Adam Banasiak, Bartosz Bartczak, Michal Gaj, Dawid Sionkowski, Michał Plotka, Mateusz Bienkowski and Wioletta Michalik.

MOS (Microsystems-Oriented Society), affiliated with the Faculty of Electronic Engineering, dealt with the electronic wiring and LED lighting control system. The team consisted of Michal Chodzikiewicz (coordinator), Liliana Cierpial, Emiliana Cierpial, Marcin Czekajlo, Piotr Falis, Igor Gajewski, Patryk Gasek, Martyna Giler, Tomasz Januszewski, Piotr Kowalczyk, Damian Krata, Daniel Majchrzycki, Grzegorz Muraczewski, Marcin Panek and Adrian Pralat (second coordinator).

LabDigiFab, affiliated with the Faculty of Architecture, was responsible for the illumination-controlling software. The team consisted of Jakub Lawicki (coordinator) and Paweł Joniak, Emil Barczynski and Bartosz Witkowski.

Students from TU Delft's Faculty of Architecture and the Built Environment participated in the construction, as well, during their stay at WUST in April 2015: Alois Knol, Arko van Ekeren, Erik van den Broek, Iris van der Weijde, Marijn Verlinde, Dion Renzo, Adhir Lachman, Eline Stubert, Max van den Berg, Maarten van der Kuur, Roman Oost and Wouter Kamphuis.

The pavilion was realised in association with partners and sponsors who contributed funds, materials and knowledge.

After the execution drawing had been finalised, the teams rented WUST's production hall. All the materials needed for construction were delivered here. Next the impregnation tests were carried out. As the paper tubes were not protected from external conditions and the weather, a waterproofing method had to be selected very carefully. Based on previous experiences as well as on tests conducted previously by the Humanisation of the Urban Environment students' organisation, several impregnators available on market were selected for testing. The specimens of the paper tubes were coated with six different products:

- Epidian – an epoxy composition.
- Syntilor – BSC varnish for wood based on polyurethane resins.
- Liquid glass.
- Domalux – yacht varnish based on alkyd-urethane resins.
- Bondex – exterior & yacht – polyurethane-based varnish used on wooden parts exposed to constant contact with water.
- Sarsil H-14/R silicone-based reagent for waterproofing walls and building materials.

The specimens were subjected to direct contact with water by means of a one-hour shower and by being put into a bucket with water for 24 hours. The results showed that the paper tubes were prone to damage caused by water in two ways. One source of vulnerability was the cut endings of the tubes, which were however protected by circular Plexiglas boards attached to either end of the tubes by silicon glue and a few thin nails. Secondly, the walls of the tubes were prone to damage. Specimens coated with epoxy resin showed good results: neither the walls nor the cut ends were damaged. However, the process of applying the coating was time-consuming. The epoxy had to be mixed before being applied to the material with a hardener. Moreover, it required a longer drying time than other impregnators. Furthermore, epoxy is harmful to people's health and to the environment (see Fig. 4.131). The second type of varnish used, Syntilor, based on polyurethane resins, covered the outer layer of the tubes quite well. However, it still allowed the cut ends of the paper tubes to be damaged by water (see Fig. 4.132). Liquid glass proved insufficiently able to protect either the outer layer or the cut ends, even if it did have the added bonus of extra fire protection (see Fig. 4.133). The Domalux product (normally used to impregnate yachts) proved unable to protect the tubes from water. The paper tube treated with this product grew soft and the layers of paper delaminated easily (see Fig. 4.134). The polyurethane-based Bondex yacht and wood varnish did well at protecting both the outer layer and the cut ends of the specimens. It changed the appearance of the tube by making it darker and shiny, but the coating seemed to be firm and well absorbed by the layers of paper (see Fig. 4.135). Lastly, the Sarsil reagent for building materials proved to be insufficiently strong. It caused the paper tube to delaminate easily and to lose its strength, allowing it to be torn easily (see Fig. 4.136).

Since the best results were achieved by Bondex, this was the team's product of choice.

FIGURE 4.131 Impregnation specimen No. 1: Epidian epoxy coating, 2015

FIGURE 4.132 Impregnation specimen No. 2: Syntilor wood varnish, 2015

FIGURE 4.133 Impregnation specimen No. 3: Liquid glass, 2015

FIGURE 4.134 Impregnation specimen No. 4, Domalux – yacht varnish, 2015

FIGURE 4.135 Impregnation specimen No. 5, Bondex – exterior & yacht varnish, 2015

FIGURE 4.136 Impregnation specimen No. 6, Sarsil reagent for waterproofing, 2015

As the paper tubes were mounted into position perpendicular to the centre of the arches, they were subjected to flat crush compression. A project partner, Corex Group, and VPK Packaging Group, producers of paper tubes and packaging materials, conducted flat crush tests on the paper tubes. These tests were conducted in accordance with the following norms: ISO 11093-1 (selecting the specimens), ISO 11093-2 (preparing the specimens) and ISO 11093-9 (strength test). Each specimen had a diameter of 100mm. Three specimens were tested, with the following results: 793N/100mm, 783N/100mm and 862N/100mm. The average flat crush test result was 813N/100mm. The expected strength was 650N/100mm +/-10% (see Fig. 4.137).

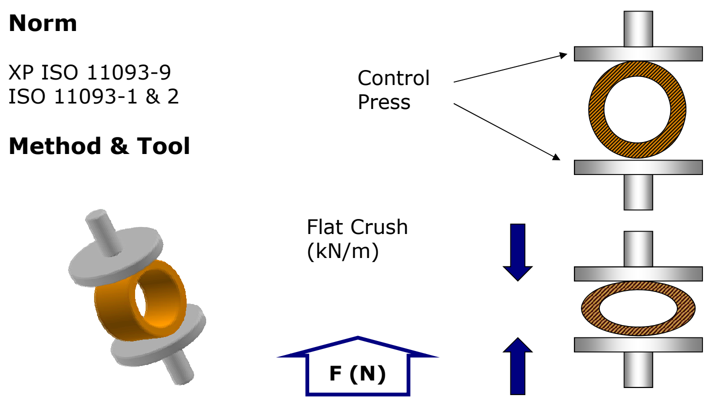

FIGURE 4.137 Schematic representation of flat crush test conducted by Corex Group, 2015

Production of the pavilion's components commenced in April 2015, when all the necessary materials were received and tests were conducted. First the paper tubes were drilled, then impregnated by dipping them into the polyurethane-based Bondex exterior & yacht varnish (see Fig. 4.138). After being dipped into Bondex, the paper tubes were hung from wires to dry (see Fig. 4.139). At the same time, the timber arches were prepared by drilling the holes for the paper tubes and other structural elements. In the initial draft, the pavilion was placed on adjustable levelling feet. However, due to the need for extra weight, the levelling feet were replaced by foundations in the form of serrated wooden beams protected from below by a rubber cloth and placed on the ground (see Fig. 4.140). The electrical wiring was placed in milled slots in the wooden arcs. Then the wooden arches were connected to the paper tubes by means of bolts (see Fig. 4.141). Although the test results indicated that the paper tubes were strong enough for a flat crush, some additional steel pipes were used against compressive and tensile horizontal forces.

FIGURE 4.138 Impregnation of the paper tubes, 2015

FIGURE 4.139 Allowing the impregnated paper tubes to dry, 2015

FIGURE 4.140 Preparing the wooden foundations, 2015

FIGURE 4.141 Electrical wiring, 2015

The assembled components were transported to the city centre one by one, then installed on Solny Square by means of a crane (see Figs. 4.142 and 4.143). Over the next three days, the LEDs were installed, as were the exhibition boards. In early May the Pavilion was opened to the public (see Figs. 4.144 – 4.148). The pavilion was incorporated into the programme for Wroclaw's European Night of Museums. After housing the exhibition on Solny Square for two weeks, the pavilion was transported to the campus of Wroclaw University of Science and Technology (see Fig. 4.149). Several weeks later the pavilion was disassembled. The paper tubes were discarded, while the wooden arcs were preserved for another experimental project.

FIGURE 4.142 Transportation of the components to the city centre, 2015

FIGURE 4.143 Placement the pavilion components on Solny Square, 2015

FIGURE 4.144 Visitors: Maria and Filip, 2015

FIGURE 4.145 Detail of the exhibition boards, 2015

FIGURE 4.146 WUST Pavilion on Solny Square, Wroclaw, 2015

FIGURE 4.147 The pavilion on Solny Square at daytime, 2015

FIGURE 4.148 The pavilion on Solny Square at night, 2015

FIGURE 4.149 The pavilion on the Wroclaw University of Science and Technology campus at night, 2015

The Pavilion realised in order to commemorate Wroclaw University of Science and Technology's 70th anniversary was an experimental project realised in cooperation with specialists from different fields of science and industry. The main challenge involved in the project was proper communication between designers, contractors, the university's administrators and other parties involved in the process. The key issue encountered in the early days of the project was accurate and precise directions. For instance, the phrases 'It will be finished soon' or 'It will take several days' turned out to have different meanings for the architect on the one hand and for the engineers associated with the Faculty of Electronical Engineering on the other. This resulted some unexpected delays setting the realisation of the project back several days. The designers and contractors also took a different approach to the aesthetics of the project. While for the architects, the purity of the structure and the natural appearance of the materials were paramount, the most important aspect to the civil engineering students was the stability and protection of the structure. Apart from these small misunderstandings caused by different styles of communication, the project was carried out smoothly and every single person involved in the project was completely engaged. Without the high level of engagement shown by the students and the University's administrators, the project would not have succeeded.

Due to time and budgetary restraints, it was impossible to conduct long-term impregnation tests on the tubes. This resulted in some paper tubes being damaged after having been exposed to natural conditions and rain for over a month. Another event the architect had not allowed for was the visitors' behaviour. Many people at Solny Square and on the university's campus treated the pavilion like a big toy. They tapped on the Plexiglas plates as if they were drums that needed to be played, which resulted in the boards falling off, thereby exposing the cut ends of the paper tubes.

Despite the aforementioned issues, the Pavilion and the process of designing and constructing it were successful, and both the designer and his team learned some valuable lessons.

§ 4.4 Conclusions

People have tried for almost 150 years to use paper and its derivatives as building materials. Different approaches have been taken over the course of time. Since machine production of paper was invented in the late eighteenth century, the material has been recognised as a cheap substitute for existing construction materials – particularly for wood. The invention and popularisation of new products in the paper-making industry, such as corrugated cardboard, paperboard and honeycomb panels, have encouraged architects and engineers to experiment with new structural and material solutions. In the 1980s, Shigeru Ban introduced paper tubes as building components, and it soon became the most popular paper-based product used in architectural structures.

Early examples of the use of paper in architecture (late nineteenth century to the late 1980s) concerned mainly emergency relief houses, especially after World War II, when there was a considerable housing shortage. Most of the projects then carried out were of a temporary nature. However, some of them lasted surprisingly long. One experimental shelter built by the Institute of Paper Chemistry in 1944, designed to last one year, ended up lasting 25 years.

Through much trial and error, other interesting proposals were made, designed to provide a proper answer to the demand for affordable housing and shelters. Such proposals included the Pappedern – recreational and utility units designed by 3H Design for the 1972 Munich Olympics.

The development of cardboard as a building material was largely the result of activities carried out by Richard Buckminster Fuller, who was always on the look-out for new and innovative solutions to the housing problem. His experiments with geodesic domes built out of cardboard panels turned the public on to the construction possibilities presented by cardboard.[28]

Approaches to paper as a building material have changed noticeably over the course of time. In the twentieth century, paper products were recognised as a material that is both cheap and easily obtained. Therefore, a great deal of work was done with regard to impregnation methods or the composition of sandwich panels made out of cardboard and other materials like aluminium sheeting, GRP, sulphur, resin or plastic coating, especially since the second half of the twentieth century, which saw the development, introduction and use of different types of plastics (e.g. films) and surface treatment as a moisture barrier. The changed composition of paper and the development of new coating methods made paper a more promising material for buildings with a longer lifespan.

In the last decade of the twentieth century, architectural requirements changed in accordance with Agenda 21, an action plan drawn up after the 1992 Earth Summit (UN Conference on Environment and Development) in Rio de Janeiro. [29] The document, which outlines the meaning of sustainable development in conjunction with a growing consciousness of the limitations of non-renewable resources, brought 'pro-ecological' architecture into general use. As a result, paper, a material produced from cellulose fibers that can be obtained from renewable resources and can be recycled up to five life cycles, gained a great deal of popularity. The Agenda 21 action plan also had an impact on the impregnation methods used. The end of the twentieth century brought us a greater understanding of paper structures, which are now recognised as being sustainable and 'green'.

Thanks to its light weight, low price and ease of production, and also thanks to its sustainable properties and rather ephemeral character, designers are now more likely to use paper in several main categories.

This thesis presents 31 projects involving paper architecture. These largely fall into four categories:

- Emergency shelters and emergency relief structures (ten projects);
- Affordable and sustainable houses (six projects);
- Structures for temporary events (five projects);

- Experimental and commercial projects (ten projects, including six permanent structures and four short- or medium-lifespan structures).

Some of the projects realised fall into more than one category. For example, the projects undertaken by Richard Buckminster Fuller could be categorised as experimental projects, but the architect always kept an eye on quality of life, and his own project was inspired by a human-centric point of view. Therefore, these projects can also be categorised as affordable and sustainable houses.

Since paper is a cheap material, most of the projects presented here were obviously emergency, relief or low-price housing structures. Actually, most of the first attempts to use paper as a structural material in architecture focused on emergency housing. Other proposals concerned short- or medium-lifespan structures that served as homes or places for social gatherings or utility buildings (Pappedern, Paper Dome). Pavilions and exhibition spaces make up another category of paper structures.

One of the biggest issues with using paper in architecture is the fact that few places have authorised the use of paper as a building material. There is barely a 'body of knowledge' where the knowledge and insights gained in successful projects are collected. Paper is barely recognised and approved as a construction material by institutions, building laws and governments. This means that every time a paper structure is going to be erected, material tests have to be conducted in order to prove its stability and safety. So far only two countries (Japan and Germany) have authorised paper as a building material, and two other countries (the Netherlands, England) have granted permission to build permanent buildings made of paper. Westborough Paper School in Westcliff-on-Sea in the United Kingdom is the earliest European example of paper being approved for the construction of a permanent structure, although the school was designed and built as a semi-permanent or medium- lifespan building, with an anticipated lifespan of twenty years. In the Netherlands, where the roof structure of Ring Pass Field Hockey Club's clubhouse is made out of paper tubes forming a space frame, authorisation by the local authorities drew upon the high trust gained by the Octatube company during several dozen years of successful activity.

It is hard to predict how certain paper products will behave, especially when they are made of recycled material. Therefore, each time a series of products is manufactured, it must be subjected to testing in order to check for quality differences in the material. The predictability of the quality of the material depends on the production process used, as well as on the source material. Therefore, it is hard to certify material whose properties can vary, even if it comes from one and the same factory. Paper and its derivatives also pose another problem, which is their mechanical properties. Creeping and vulnerability to humidity, water and fire are the most problematic issues. There are no known examples of paper structures being used to construct multi-storey building. It may be assumed that paper should only be used for structures of single-storey buildings.

§ 4.4.1 Types of the buildings and characteristics

Most paper structures that have been realised so far are temporary ones. Their lifespan ranges from several weeks (Apeldoorn Theatre) to several years (Hualin Primary School). Only few buildings have been erected to be permanent structures or have a medium lifespan (up to twenty years). This is because the material has not yet been authorized by the building industry, and because of the short-lived nature of paper. For example, the paper tubes used to construct Hualin Primary School have to be painted every year. The recyclability of paper that gives it such a temporary nature provides us with a wide range of opportunities with regard to short-lifespan houses or temporary structures. The other possibility is to use cardboard as a primary (temporary) structure which can be later reinforced with another material, e.g. concrete sprayed onto a cardboard mould. A characteristic feature of permanent buildings is that their paper structural elements are never exposed to the elements. Rather they are used as internal structures, covered by other parts of the building.

Out of all the projects presented in this chapter, only four were made in large quantities. No fewer than one thousand versions of Plydom accommodation for seasonal workers (1966) were produced. Paper Log House was erected in four different locations, with the house differing slightly from its previous incarnations each time, depending on local conditions. The idea of the Paper Dome was employed in four different projects: Dutch Paper Dome, Keio University's Ban Lab Studio, Shigeru Ban's temporary office at Centre Pompidou, and Shigeru Ban Studio at Kyoto University of Art and Design. Each time it was adapted to new conditions. Lastly, Wikkel House is promoted as the first series-produced cardboard house in the world. Many attempts at getting large projects off the ground got stuck in the prototype phase and did not succeed because of a lack of interest on the part of potential stakeholders, or because the market was not ready for it. Furthermore, many potential clients, not to mention local authorities, distrust the reliability of paper and cardboard as a building material. Therefore, the promotion of paper as a sustainable and affordable material should run parallel to new experiments and developments.

§ 4.4.2 Structural systems

There are three different structural systems with which cardboard architectural elements can be realised [30]: 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).

§ 4.4.3 Paper products and their use in building

The paper and paper-derived products used in architectural structures are corrugated cardboard, paper board, honeycomb panels and paper tubes. These elements were previously described in Chapter 2.

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 the paper structure is enhanced with other building components. Although there is a challenge to use as much paper as possible in order to make the structure more eco-friendly or cheap, this architectural Puritanism is not always found profitable.

Plate products like corrugated board or honeycomb panels work efficiently as wall or roof elements, whereas paper tubes can be used most efficiently when employed as load-bearing slender structures. However, plates can also be used as structural elements of a building when they are incorporated with other members, as shown in the Westborough School or Nemunoki Children's Art Museum. In Apeldoorn Theatre, corrugated cardboard was used as a load-bearing material that covered a 12m span. However, when a greater span is required, usage of more slender and stiffer elements is recommended. On the other hand, the Paper Log House project showed that paper tubes can also be turned into a wall component by being placed right next to each other. Although the paper tubes were rendered more rigid by means of crumpled paper (in Turkey) in order to benefit from the thermal insulation, the connection between the tubes was linear and thus thermal bridges came into being. Plate products, when used as a 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, fibre boards or plastic foils 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. In the Japan Pavilion created for Expo 2000, two long paper tubes (each 20m long) were connected, while 40m long elements were used as structural components. Due to the risk of paper tubes creeping over time, the structure was strengthened with timber-laminated ladders serving as a sub-supporting structure, thus ensuring that the cardboard tubes were a secondary rather than a primary structure. This was enough to guarantee the structure a five-month lifespan. Another example is the Cardboard

Cathedral in Christchurch, New Zealand. Designed by Shigeru Ban for a city that was greatly damaged by a 2013 earthquake, the church has a roof made out of 16m long paper tubes with a diameter of 600mm. Since the material was not strong enough to carry the loads, wooden beams were inserted into the paper tubes (see Fig. 4.150).

FIGURE 4.150 Cardboard Cathedral in Christchurch, New Zealand, Shigeru Ban, 2013

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 the Miao Miao Paper Nursery School project, the paper tubes were aligned with wall panels made out of plastic sashes. This resulted in relatively long roof eaves that had to protect the tubes from the rain. The opposite can be seen at Ring Pass Field Hockey Club, where all the tubes making up the space frame are inside of the building. Therefore, the tubes did not require heavy coating. In fact, some of them were left untreated by way of test. Moreover, in the Miao Miao building, there are few connections between the paper tubes and the wall panels, since the paper tubes are round in section, while the wall panels are square. Additional wooden battens had to be screwed into the paper tubes to make sure the wall panels could be installed.

§ 4.4.4 Connection types

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-tensioned elements**
4. **Interlocking**
5. **Folding**
6. **Clipping/tiding**

The process of lamination appears to be the most suitable connection for paper and cardboard. As far as strength is concerned, the layers of the material are best connected when the layers are laminated surface by surface. Different types of glue are used for this purpose. The most popular type is PVAc glue (polyvinyl acetate), also known as wood glue. There are four grades of wood glue, with grade 4 being waterproof. Other adhesives like epoxy, phenol-formaldehyde and polyurethane like PVAc are based on non-renewable resources. The natural bio-based adhesives are polysaccharides and proteins. Both are commonly used in paper production. Currently the development of polysaccharides is prioritised due to their natural origin and structural variability. As polysaccharide adhesives are not intrinsically waterproof, the chemical industry is placing great emphasis on research on this particular subject. [31] Another adhesive is liquid glass, which is used for the production of certain types of paper tubes. Liquid glass is not only used for its adhesive properties; it is also used in fireproof products. However, liquid glass also comes with a disadvantage, which is that during the lamination process it often requires special treatment (e.g. a drying chamber). Furthermore, it is time-consuming.

In the project of the paper house designed and built by Paul Rohfls, structural elements like walls and parts of the roof were laminated. The corners of the walls were first folded, then glued. The walls and parts of the roof were composed of laminated honeycomb panels. In the Westborough Primary School project, the honeycomb wall panels were laminated to the wooden frames. The frames were later connected with each other and other components of the building by means of simple screws. Likewise, the process of lamination played a prominent part in Wikkel House, whose walls, floor and roof are made out of laminated layers of corrugated cardboard. Although lamination is the most natural way to treat paper structures, it is time-consuming. The Wikkel House case showed that proper drying time is vital to the strength of the structure, with corrugated cardboard that had not yet completely dried proving to be almost twice as weak as corrugated cardboard that had been allowed to dry properly.

Screw/bolt connections between paper or cardboard elements have their pros and cons. Paper is weak when point loads are applied. Thus the structural elements or components have to be connected by means of specially designed joint elements. If we look at the paper buildings that have been realised thus far, we will find that this type of connection has been the most popular. The joint elements may be plates that are clipped to both sides of the paper (plate) elements, or alternatively, they may be boxes, pegs or planks that are inserted into or between the paper elements. The joints can be made out of timber, aluminium or steel. Other materials such as cast cardboard or other composites may be used, as well. However, paper itself has never been used as part of a connection because of the concentrated forces exerted on the connector. Connections involving screws are disposable. Once a screw has been drilled into the wood, it is not possible to re-use it since the thread of the relatively soft material has been damaged. Bolt connections are re-usable. In his first three structures based on the principle behind the Paper Dome, Shigeru Ban used timber connectors and screws. In the Kyoto University of Art and Design studio, the architect used steel plates as he knew that the building was just temporary and would be moved to another location after his dismissal from the University. It is also important to pre-drill paper elements when using screws and bolts. Pre-drilled holes have to be impregnated before actual construction can commence. Another issue that may occur when connecting paper with elements made of steel, such as screws or bolts, is condensation and the capillary effect caused by the differences in temperature between the cold steel elements and the warmer paper components. To prevent this from happening, an air cavity should be created, and screws should be inserted from the inside i.e. the warmer side. The connections between cardboard elements such as paper tubes and timber joints can be flexible if the structure is built in an area that is prone to earthquakes. However, this often requires additional bracing of the entire structural system. Another issue is the cost of connections. Timber joints are relatively cheap and can be produced manually (as was the case in the Miao Miao Nursery School project) or in a more industrialised setting, by means of computerised cutting of plywood. On the other hand, steel or aluminium joints have to be cast, and they may well end up heavier and more expensive than the paper structural elements. Last but not least, timber is a material that used to live, meaning it has a special aesthetic connection to paper.

Post-stressing or post-tensioning cardboard elements like paper tubes has proved to be an efficient way to connect elements, because the paper tubes do not have to be connected by bolts or screws. As a result, point loads are avoided and the paper tubes do not need to be pierced. In the first permanent structure in which paper tubes were employed as load-bearing elements (the Library of a Poet), post-tensioned bracing was used. Threaded rods run through the paper tubes as well as diagonally from the wooden joints. A similar solution was applied in the Demountable Paper Dome and Ring Pass Field Hockey Club, but in these projects the elements were post-stressed before being combined with joints. In this type of connection, the tubes are subjected to compression forces, so there is never any tension, which is the best way of make use of their properties. Although this type of connection is effective, it is limited to products like paper tubes. For its part, post-tensioning of building components was used in the Paper Log House and Wikkel House. Paper Log House's wall, composed of paper tubes, was tensioned by a steel rod that ran horizontally through the paper tubes. In the case of Wikkel House, whole segments were connected to each other by a tensioned threaded rod.

Interlocking is an easy type of connection and does not intrude on the material. However, connecting the building components by interlocking requires material with the right level of stiffness and thickness. The case of the Cardboard House built in Sydney shows a wine-box-like connection, which can be assembled and disassembled by several people in a few hours. However, this type of connection has to be reinforced by additional elements like plates or canvas that will not allow the elements to slide out of each other. Furthermore, when the interlocking connection method is used, point loads may occur.

The last two types of connections – folding and clipping/tiding – are the least effective. As far as the aforementioned case studies are concerned, the Japan Pavilion for Expo 2000 is a representative of this type of connection. Its long, overlapping paper tubes were connected by fabric tape to allow three-dimensional movement and rotation during the erection process. The tape worked mostly against shear forces.

§ 4.4.5 Connection with the ground

The permanent paper structures presented in the case studies were predominantly built on concrete foundations. However, sometimes the amount of concrete used can give a wrong impression of how sustainable the paper-based structures actually are. The case of Westborough Primary School, whose concrete slab amounted to 85%

of the weight of the whole building, shows a significant disproportion and deviation from the architects' original idea. On the other hand, 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 nature are lightweight, the role of the foundation is dual: to keep the structure in its place against the wind loads and the forces caused by things such as earthquakes and to protect the cardboard structure against moisture from the ground or surface water.

§ 4.4.6 Impregnation

Another challenging aspect of working with paper structures is the method used to impregnate the various components. As mentioned above, paper is vulnerable to water and moisture. As a hygroscopic material, paper can absorb water from the humidity in the air. Direct contact with water affects the bonds between cellulose fibres. In the process of hydrolysis, cellulose fibres are loosened up and paper turns into pulp. Therefore, since architects first began to use paper as a structural material, different methods have been used to impregnate the material. The position of the paper elements and components in the building plays an important role. It is advisable to place structural elements made of paper inside the building, so they can be protected from the elements by the enveloping structure that is the building.

The optimal moisture content of paper is between 5% and 7%. When the moisture content reaches 13%, the strength of the material is dramatically reduced. At a relative humidity level of 60%, the material's moisture content rises to 9.5%. At a relative humidity level of 90%, the material's moisture content increases to 15.8%, and the strength of the paper is reduced by one-third. The strength of paper is affected by differences in both temperature and humidity levels.

When working with building components like walls or roof panels which are made of paper elements, it is important to protect them from being damaged by moisture transported through the material. The transfer of moisture caused by differences in temperature inside and outside the building may cause condensation within the envelope. Therefore, a vapour barrier should be applied inside the building, while a water-resistant barrier should be installed outside. The most critical parts are cut edges and drilled holes. They must be treated particularly carefully with an additional layer of impregnator or special products that will protect them from moisture.

Another issue that must be addressed is ensuring that the paper and cardboard used are fireproof. Products like corrugated cardboard or honeycomb panels are composed of relatively thin layers of paper. Therefore, they are flammable, and a fire retardant must be applied to their surface. However, when a solid board or paper tubes are subjected to flames, a layer of carbon will form that will protect the underlying material from burning.

The impregnator applied to the paper elements should also protect them from other threats like UV, fungus, micro-organisms and rodents.

There are several different ways to impregnate paper products:

1. **Coating** – a layer of coating is applied to the product after manufacturing in the factory or on the building site. The 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.

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

3. **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.

4. **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. However, products such as paper tubes may be recycled once their outer protective skin has been delaminated.

The chemical and paper industries are currently developing more new solutions for the impregnation of paper products. As this dissertation focuses on paper as a building material from an architectural and structural point of view, and particularly focuses on the details of the structure, it will not describe impregnation-related aspects in great detail. Although some information on the various impregnation methods is provided, they should be more thoroughly investigated by researchers and scientists specialising in chemistry and the production of paper.

§ 4.4.7 Processes of design, research and construction

Due to the legal issues inherent in the use of paper as a building material, the process of designing, researching and developing paper architecture must be conducted carefully. Fundamental technical research on the technology of paper and cardboard production and the design of a suitable structural system all have to be undertaken simultaneously. [13] During the design stage, when developing a new type of structure or structural details such as connections, a 1:1 scale mock-up of the building or a part thereof may be vital and useful. Prototyping is easy and extremely helpful. Furthermore, it is vital that the condition of the construction site be thought through. For example, if there is a risk of rain while construction is ongoing, the building site, or parts of the building, must be temporarily covered. Affordable transportation of the components and the distance between the manufacturing factory and the building site are important factors from a project profitability point of view. The high costs of prototype building have to be taken into account. Therefore, right from the start of the design and development process, architects should consider using elements previously produced by the paper industry and create a strategy for the further implementation of paper based materials to be used in architecture. Turning the paper industry onto paper architecture could be beneficial for the sake of material and knowledge support. The paper industry is a fast-growing branch. Therefore, investments in new and innovative ideas can be put to good use by researchers, designers and the industry. The key task is to promote proper communication between the paper-making and building industries and finding a niche market to compensate for the investment in facilities to make it commercially viable. Although it seems likely that the demand for small amounts of paper products with high quality requirements will only appeal to a few cardboard manufacturers.

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

I tell you the truth, when you refused to help the least of these my brothers and sisters, you were refusing to help me

Gospel of Matthew (25:45) [1]

§ 5.1 Introduction

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 [2] 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 (see Fig. 5.1.).

However, in addition to the forcibly displaced people, there are many people who lost their homes because of natural disasters, and those 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 affected people. [3] 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. [4] As it is very hard to define or recognise a homeless person, this number may be 'off' by quite a significant margin.

Since 2015 there has been a large influx of people from the Near East and African countries in Europe. This influx has caused the largest migration crisis since World War II. By the end of 2016, Europe was hosting approximately 10.2 million of people of concern, including 6.6 million asylum seekers and refugees, 3 million internally displaced persons (including returnees) and more than 570,000 stateless people. [5] There is a lot of debate on the subject of refugees and immigrants and on the policies in place to help them. However, the political discussion on this is beyond the scope of this work, so the author will not comment on it. The focus of this part of the thesis is on potential architectural solutions for people who find themselves in a difficult housing situation, for whatever reason.

In this thesis, emergency and relief architecture is understood to refer to structures, buildings and infrastructure that support people in need, such as forcibly displaced people, victims of natural disasters or homeless people.

Each of the aforementioned groups requires a different approach with regard to safety, policy and medical or psychological support. Each group is also characterised by different factors. In order to understand the differences, so as to be able to provide the right type of support, it is important that we gain an insight into the characteristics of each group.

Both emergency shelters and temporary houses can be made out of paper components. Depending on the situation, they can be either temporary or semi-permanent shelters or buildings.

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§ 5.2 Victims of human-made and natural disaster, and the homeless

In a way, all the aforementioned groups (forcibly displaced people, victims of natural disasters and the homeless) living in developed countries can be called homeless. However, homelessness is a very broad and complex problem, in which many factors are at play, depending on the homeless person's cultural background, political situation, and most importantly, personal situation. Homelessness can be described as a situation in which a person, for whatever reason, lacks a proper place to stay. This definition does not indicate whether a person is in danger caused by others or by natural conditions, nor whether s/he was excluded by society and lives on the margin of society.

There are many different reasons why people become homeless. If we look at global housing problems, three key groups can be distinguished: people who were forced to leave their homes because of persecution or warfare, people who lost their homes due to natural disasters, and people who were excluded from society and so became homeless.

§ 5.2.1 Forcibly displaced people

In the year 2016, 22.5 million out of 65.6 million forcibly displaced people were refugees or in a refugee-like situation. Of these, 17.2 million were under UNHCR's mandate and 5.3 million were Palestinian refugees registered by UNWRA (the United Nations Relief and Works Agency for Palestine Refugees). In addition to the refugees, there were 40.3 million internally displaced persons (IDPs) and 2.8 million asylum seekers, who submitted 2 million applications for asylum (see Fig. 5.1). [2]

The aforementioned categories come with the following definitions:

- **A refugee** *is a person who as a result of events owing to well-founded fear of being persecuted for reasons of race, religion, nationality, membership of a particular social group or political opinion, is outside the country of his nationality and is unable or, owing to such fear, is unwilling to avail himself of the protection of that country; or who, not having a nationality and being outside the country of his former habitual residence as a result of such events, is unable or, owing to such fear, is unwilling to return to it.* [6] The status of refugee described by the United Nations Convention and Protocol shall not apply to persons who are receiving protection and assistance from organs or agencies of the United Nations, other than the UNHCR. The term 'refugees' also includes those in a refugee-like situation.
- **Internally displaced persons** (IDP) *are people or groups of people who have been forced to leave their homes or places of habitual residence, in particular as a result of or in order to avoid the effects of armed conflict, situations of generalized violence, violations of human rights, or natural or man-made disasters, and who have not crossed an international border. For the purposes of UNHCR's statistics, this population includes only conflict-generated IDPs to whom the Office extends protection and/or assistance. The IDP population also includes people in an IDP-like situation*. [2]
- **Asylum seekers** (with 'pending cases') *are individuals who have sought international protection and whose claims for refugee status have not yet been determined*. [2]

FIGURE 5.1 Trend of global displacement 1997-2016 [2]

All three groups require a different approach and different treatment.

Refugees

Refugees, being people who have been officially granted that status, should receive assistance and protection from UNHCR, non-governmental organisations and governments, which should bring them relief and possibly help them be assimilated into their new surroundings and society, thus helping them become self-sufficient. Refugees should possess the right to work, earn money, get an education, enjoy freedom of movement within the hosting country and receive public support, assistance, health care and social security in the country in which they are staying. Refugees who have unlawfully entered their host country shall have a right to apply for asylum. As the Convention and Protocol relating to the status of refugees states, The Contracting States shall as far as possible facilitate the assimilation of the refugees (art. 34), which may or may not end in their becoming naturalised citizens [6]. As far as housing is concerned, refugees shall possess the same rights as any alien lawfully staying in the territory of the contracting state. The protection of refugees has many aspects. These include safety from being returned to the dangers they have fled from; access to asylum procedures that are fair and efficient; and measures to ensure that their basic human rights are respected, so as to allow them to live in dignity and safety while helping them to find a longer-term solution. States bear the primary responsibility for this protection.

Internally displaced persons (IDP)

People who have been internally displaced due to conflict or violence retain possession of their rights in the same way they did before leaving their homes. Such people remain under the protection of their own state, even if the state was the reason for their displacement in the first place. UNHCR's mandate does not specifically cover IDPs. IDPs are among the most vulnerable people in the world. In less developed states IDPs have little support and few means to meet their short-term needs. IDPs flee from conflict regions to urban and rural areas. In urban areas they stay in private accommodation and the duty of assistance falls on their host community. Such situations may raise the tension between the IDPs and local communities which often already lack the resources required, resulting in new conflicts and further displacement. In rural and sub-urban areas IDPs stay in planned camps, self-settled camps or collective centres. Many IDPs who live in protracted displacement are in time left neglected because the media attention, donors and regional and international responders all dwindle. [7]
In rural areas IDPs can stay in two types of camps: either organised and planned or spontaneous and self-settled.

Asylum seeker

An asylum seeker is a person who has not yet been granted 'refugee status' and therefore does not possess the same rights as a refugee, e.g. a residence permit. Asylum seekers are people who claim refugee status but whose final evaluation is still pending. In the years 2015 and 2016 there were 1.3 million asylum applications in the European Union each year. After a refugee arrives in a country, s/he is entitled to apply for asylum. The procedure behind this application involves several steps.

The asylum application process will be described below on the basis of Dutch legislation, which was broadly explained by Naisa Al Kailany (2016) in her Master's thesis entitled Refugee Influx. Using the Existing Buildings to House Asylum Seekers [8] as well as on the web page of the Dutch Ministry of General Affairs (see Fig. 5.2.). [9]

First, newly arrived refugees must apply for asylum in one of the asylum centres. For the next few days (minimum of six days) they will rest and prepare for their interview. During that time, they can stay at the Central Reception Centre (COL) or at the Application Centre at Schiphol Airport. During this period the Central Agency for the Reception of Asylum Seekers (COA) is responsible for the reception, supervision and departure (from the reception centre) of asylum seekers. The application/registration procedure at the COL takes three days. During this procedure the asylum seeker has to complete a form, his fingerprints are taken and he is interviewed regarding his identity, family members, travel route and profession. After at least six days, the asylum seeker is relocated to the Process Reception Centre (POL), where s/he attends an interview, during which s/he explains his/her situation. After the interview, the Immigration and Naturalisation Service (IND) assesses the application. If the decision on the refugee's status requires more investigation and information, the asylum seeker is transferred to an Asylum Seekers' Centre, where s/he is subjected to further investigation. The aim is for applicants to leave the Centre within a year. However, as Al Kailany reports (2016), in 2011 more than half of the applicants stayed over a year. If the IND establishes that an asylum seeker needs protection, s/he will be given an asylum residence permit. The first permit is temporary and is granted for a term of five years. If the situation in the asylum seeker's home country improves during this period, his/her permit will not be extended. If the situation in his/her home country continues to be unsafe, the refugee will receive a permanent residence permit, which cannot be repealed.

Asylum seekers who do not require protection must return to their country of origin. They are transferred to a Return Centre, where they are allowed to stay for up to twelve weeks. Once the voluntary return period ends, they can stay at a location where their freedom is restricted. If a rejected asylum seeker does not leave the Netherlands, s/he runs the risk of becoming homeless. [8]

Depending on their country's current situation and their own capacities, asylum applicants will stay at an Asylum Seekers' Centre (AZC, i.e., a regular reception centre), Emergency Reception Centre (temporary reception facility in case of room shortage at asylum seekers' centres) or Crisis Reception Centre (generally a sport facility temporarily turned into a reception centre by a local government), where asylum seekers can stay for a very short period of time – generally, a maximum of 72 hours. The latter type of reception centre is not in use currently.

COA can establish both permanent and temporary Asylum Seekers' Centres. The most cost-efficient centres (AZCs) are centres housing 400-600 persons, which are built to last fifteen years. AZCs can be built on land owned by COA or on rented land. Temporary centres are often located in repurposed buildings, e.g. former prisons, retirement homes, monasteries, offices or barracks formerly used by the Ministry of Defence. [8] In such buildings, lightweight paper partitions can be used to divide the space temporarily into smaller apartments.

Asylum Seekers' Centres are established by the local authorities and tend to be vacant plots designated for dwellings or vacant buildings that have been adapted to house people. The inhabitants of asylum centres have rights as well as obligations. The housing of asylum applicants is organised by COA. Applicants are divided in accordance with certain rules. Family members are placed together, and where possible, the applicants will be placed with people who have the same nationality. Asylum applicants are not obliged to stay at the reception centres. However, they have to register at a reception centre once a week. Children and teenagers aged between 5 and 16 are obliged to attend school, and adolescents aged between 16 and 18 are obliged to study for initial qualifications. [8]

When an application is granted, the applicant receives a temporary residence permit and may also receive temporary or permanent accommodation in the subsidised rental sector or in another repurposes vacated (office) building. Alternatively, s/he may be assigned to a mobile living unit, holiday home, etc. The local authorities decide where refugees will be resettled on the basis of the size of their family, country of origin, language spoken, education, work experience and medical condition.

Since the number of asylum seekers municipalities receive and the organisation of their accommodation is determined by the local authorities, they can vary and it is difficult to establish one solution or guideline for the AZC design. However, the best solution is a centre built for 400 to 600 people which is intended to be used for fifteen years. Smaller residences housing 50 or 100 people can also be established by the municipalities. There is a need for asylum seekers' centres for people whose applications are pending as well as for people who have been granted refugee status and temporary resident permits valid for five years.

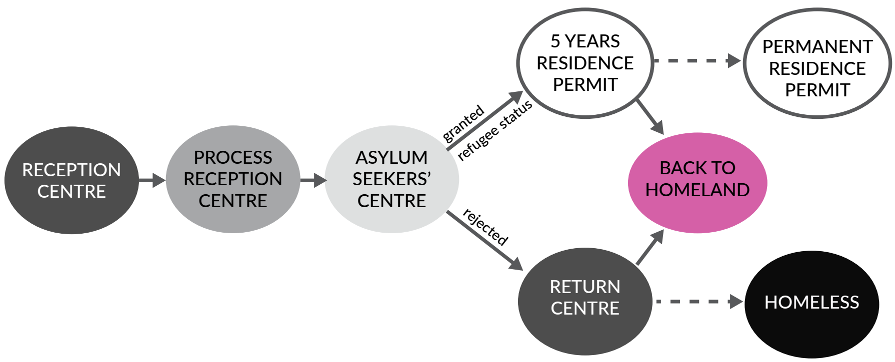

FIGURE 5.2 Asylum procedure in the Netherlands

The above describes the situation in the Netherlands, in northern Europe. The situation is quite different in the frontline EU member states – particularly in Italy and Greece, which received 1,049,400 and 374,318 refugees in the years 2015 and 2016, respectively. [10] Refugees and migrants who arrived in the EU by illegally crossing borders have predominantly used two routes: the Eastern Mediterranean route (mainly from Turkey to Greece over land or by sea) and the Central Mediterranean route (mainly from Libya to Italy by sea). In the year 2015, over one million people came to Europe by sea, 3,770 of whom died in the Mediterranean Sea during the crossing. Although in 2016 the number of people arriving by sea decreased, the number of dead or missing people reached 4,899 by the end of 2016. The European Commission adopted the European Agenda on Migration in 2015 and established a Hotspot approach to the refugees arriving on the shores of Italy and Greece. The aim of the 'Hotspot' approach is for the EU agencies to provide comprehensive and targeted support to frontline member states that are faced with disproportionate migratory pressure at their external borders. [11, 12]

Hotspots are temporary relocation places in which asylum seekers are identified in the EU member state where they originally entered the EU. In order to share the burden between the various EU countries, the asylum seekers are then moved to another EU member state that bears responsibility for processing their applications. The newcomers are swiftly identified, fingerprinted, registered and subjected to further migration procedures (i.e. the asylum application), or alternatively, they are returned to their home countries in the event that they cannot produce sufficient evidence that they require protection. Operational support consists of registration and screening of illegal migrants, debriefing of incoming migrants, further investigations, legal support or assistance with the procedure by which asylum countries are returned to their countries of origin. In Italy migrants spend a few days at the hotspots before being transferred to reception centres, whereas in Greece the hotspots serve as both reception and detention centres where people stay for a longer period. [12]

Successive actions are undertaken in hotspots or during the transfers from boats or ports to the centres, such as medical screening, dividing asylum seekers into groups according to their nationalities, gender, vulnerabilities and medical needs, providing preliminary information, pre-identification, debriefing interviews, registration and further identification.

As the hotspot approach is still a fairly new procedure, its operation is fraught with difficulties. First of all, the poor conditions in the overcrowded reception centres tend to result in stress, frustration and poor hygiene. The procedures are often slow and protracted and the reception centres do not provide asylum seekers with sufficient information. As a study on the implementation of the hotspots in Italy and Greece (2016) suggests, several improvements should be instituted. For instance, the remaining hotspots should serve as open facilities where people cannot be detained for longer than 48 hours (the constitutional limit) (in Italy), and the quality of life at reception centres where people stay longer must be improved (in Greece). Furthermore, conditions and asylum procedures at the reception centres must be monitored, reception centres must provide sufficient information, there must be more cultural mediation, and unaccompanied minors must be moved to safe places. [12]

The main reasons for the enormous number of forcibly displaced people were persecution, conflicts, generalised violence and human rights violations caused largely by the 'Arab Spring', which started in 2011. Furthermore, new or reignited conflicts in countries such as Ukraine, Burundi, Iraq, Libya, Niger and Nigeria, and unsolved conflicts in Afghanistan, the Central African Republic, the Democratic Republic of Congo, South Sudan and Yemen contributed to the global increase in forced displacement. More than half of the total number of refugees comes from three countries: Syria, Afghanistan and Somalia. It is important that we understand the cultural background of the forcibly displaced people in order to prepare conditions for them that will not cause conflicts within the group – conditions that the displaced people can adjust to.

Out of the 22.5 million refugees or persons in a refugee-like situation, 17.2 million were under UNHCR's mandate, 5.2 million were residing in Europe and 5.1 million were in Africa. The country that hosted the largest number of refugees was Turkey (2.9 million), followed by Pakistan (1.4 million), Lebanon (1.0 million), Iran, Ethiopia and Jordan. The ratio of refugees to population was the highest in Lebanon, where one in six people was a refugee, followed by Jordan and Nauru. It is clear that the countries that host the biggest number of refugees (13.9 million, i.e. 62%) are developing nations. Some of the least developed countries in the world provided asylum to 4.2 million refugees, i.e. 19% of the global total. Of the refugees from the five countries that produced the greatest number of refugees, most found safety in a neighbouring country. This indicates that most refugees are hosted by neighbouring and developing countries, and it underlines the importance of supporting the refugees in these states. The above data show not only the warm hearts of those who have the least, but also that major help for refugees should be directed to less developed and poorer countries that host refugees, preferably in such a way that they will be able to support their own economy while supporting others, for example by local production based on local resources.

It is estimated that 11.6 million refugees, i.e. 57% of those under UNHCR's mandate, were considered to be in a protracted displacement situation at the end of 2016. A 'protracted situation' here refers to people being in exile for five or more years. Out of the 11.6 million refugees, 4.1 million were in a situation lasting twenty years or longer. More than 2 million refugees from Afghanistan in Pakistan and the Islamic Republic of

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Iran have been refugees for more than thirty years. There were 5.6 million refugees who had been in exile between five and nine years. The duration of refugees' stay in their place of refuge is calculated using a method that looks at the year of the first arrival of a group (more than 25,000 persons) of refugees of a certain nationality in a country providing asylum, then estimates the average duration of the stay of all refugees of that nationality. The average duration of some 32 protracted refugee situations is about 26 years. However, 23 out of these 32 situations have lasted for more than twenty years. This means new generations of people have been born and raised in refugee camps.

It also means that emergency shelters designed to be used only during a period of transition may end up being used for much longer than expected. Therefore, they should be designed for a matter of easy replacement or possible upgrade to a permanent state. They should not be allowed to be used longer than originally intended. It is important to note that each group of forcibly displaced persons encounters different conditions, depending on their legal situation, the relation to their adopted society they say in, rights, distance to place of origin, understanding of the culture, and many more factors which have a great impact on the design thinking for social innovation.

The number of refugees who fled to European countries in 2015 increased by 1.3 million, which was 41% more than in 2014, for a total of 4.4 million. By the end of 2016, there were 2.9 million refugees in Turkey and 2.3 million in other European countries.

However, not all the people who come to the European Union are refugees and asylum seekers. There are economic migrants among them, as well. Economic migrants are persons who leave their own country to work in another country. Economic migrants are not refugees. It is difficult to estimate the number of economic immigrants who come to Europe and ask for asylum, since proper policy and careful investigation are largely non-existent in Hotspots or other places where refugees first enter Europe. It is uncertain how many economic migrants there are among the genuine refugees. Frans Timmermans, the first Vice-President of the European Commission, said in January 2016 that 'more than half, 60%, of the people who are coming to the European Union are economic migrants and have no reason to ask for refugee status. In the main, they are people from Morocco and Tunisia who want to travel to Europe via Turkey.' He also said that 'it was important to send these "economic refugees" back home as quickly as possible 'to make sure that support for people fleeing war is not harmed'. [13]

During 2015, a mere 201,400 refugees returned to their countries of origin. This number increased to 552,200 in 2016.

The gender distribution of first-time asylum applicants in the European Union shows that more men than women have sought asylum. Among the younger age groups, males accounted for 55% of the total number of applicants in 2015. There was a greater degree of gender inequality for asylum applicants aged 14-17 or 18-34, in which groups around 80% of applicants were male, with this share dropping to two-thirds in the 35-64 age group. Across the EU-28, gender distribution was most balanced among asylum applicants aged 65 and over, where female applicants outnumbered male applicants in 2015, although this group was relatively small, accounting for just 0.6% of the total number of first-time applicants. [14]

By year-end 2016, half of the refugees in the world were children and teenagers aged 18 or less.

The European Union wants to contribute to a better reception of refugees in safe countries in troubled regions, for instance Turkey and Jordan, so that refugees can find protection there. In this way the government wants to prevent refugees from falling victim to people smugglers or risking their lives on dangerous boat crossings to Europe. [9]

The European Union announced in April 2016 humanitarian funding worth €83 million for emergency support for refugees in Greece. This support includes shelters, food, hygiene, child-friendly spaces, education, family reunification assistance and protection. [15]

Since the beginning of the crisis in 2011, the European Commission has provided a total of €455 million to assist refugees in Turkey, but Turkey's whole budget for refugee facilities is €3 billion. The annual EU aid budget in 2015 and 2016 was doubled and reached €10.1 billion, of which €3.9 billion is dedicated to funding aid inside the EU and €6.2 billion is dedicated to helping refugees and internally displaced persons (IDPs) outside the European Union, particularly in the countries and regions from which most of the refugees who have arrived in the EU originally hail: Syria, Iraq, Afghanistan, Pakistan, the Horn of Africa and the Sahel.

Movements of individuals and groups during a crisis are often rapid and unpredictable. Immediate first aid is crucial, yet all the statistical data that are collected are important because they help aid organisations provide the proper solution in the form of accommodation, needed supplies and restitution and emergency programmes. This socio-economic information includes the following: date and place of birth, language, occupation, marital status, religion, highest level of education, sex and age. This kind of statistical data is unavailable in many regions. The data collected by UNHCR by the end of 2016 shows that globally:

- 49% of the refugee population were women
- 51% were children
- 45% are described as being of working age, i.e. aged between 18 and 59
- People aged 60 years and over accounted for 4%

Emergency and relief solutions vary depending on the region, the refugees' place of origin andthe policies of the host country.

The data provided above are based on information released by governments, non-governmental organisations and the UNHCR. [2, 15]

§ 5.2.2 Victims of natural disasters

In addition to the most significant refugee crisis since the end of World War II, there are millions of people who have fallen victim to natural disasters.

As the authors of the World Disaster Report 2016 stated, *the best actions are people-centered, and [...] pre-disaster investments to reduce or even prevent crises are essential*. [16]

Although global poverty was reduced at the end of 2015, there were still 836 million people living in extreme poverty.

The last thirteen years have been full of enormous destructive events happening. At the end of 2004, the Boxing Day tsunami in Asia killed approximately 230,000 people across fourteen countries. The 2010 floods in Pakistan directly affected around 20 million people, and have continued to displace substantial numbers each year. In regard to drought, during 2011 and 2012, more than 12 million people in the Horn of Africa were severely affected in what has been called the worst drought in sixty years. The Ebola outbreak in West Africa, beginning in March 2014, led to 11,310 deaths across Liberia, Sierra Leone and Guinea (WHO, 2016). The Haiti earthquake of 2010 provided a terrifying 'perfect storm' of a major earthquake striking one of the poorest countries in the western hemisphere. The population loss, of between 100,000 and 316,000 (the uncertainty of the figure highlighting the precarious governance of the country), served to illustrate weaknesses in urban areas ill-prepared for such disasters, and an aid sector also unequipped for the urban challenge. Other large-scale disasters, such as Japan's 2011 Tohoku earthquake and tsunami and the Philippines'

2013 typhoon Haiyan, as well as numerous smaller disasters triggered by natural phenomena reinforce the increasing threat of such events. The number of disasters continues to rise, as a result of a combination of increased vulnerability (since more people live in dangerous places) and climate change.

During 2015, a total of 574 reported disasters, caused by earthquakes, floods, landslides and heat waves, killed almost 32,550 people, affected over 108 million people and caused USD 70.3 billion in damage.

The World Disaster Report 2016 also referred to a 50% global increase in carbon dioxide emissions since 1990, the continued destruction of rainforests, overexploitation of marine fish stocks and water scarcity that affects 40% of humanity, which is ‘projected to increase’. The year of 2015 was described as the hottest year in history.

Armed conflict is not like an earthquake or a flood; it is entirely man-made and, by design, dismantles mechanisms for resilience. Conflict inflicts psychological trauma, separates families, divides communities, eradicates livelihoods, destroys infrastructure, diverts public funds from social services and leaves behind explosive remnants of war, all of which will undermine resilience long after the fighting has ended. Armed conflict is the flood that ebbs and flows for years or decades, eroding protective systems in the process. [16]

In most cases the help provided to victims of natural disasters takes place in the affected areas, so that the people involved are not forced to move elsewhere and abandon their connections and affiliations with other locals. Therefore, any architectural support provided to victims of natural disasters must focus on an immediate response, although the help provided can be long-lasting and become a new starting point for their lives.

§ 5.2.3 Homeless persons

Homelessness is a social phenomenon and psychological state occurring worldwide. In social terms, homelessness means exclusion. Homelessness involves exclusion from the physical area, i.e. a lack of home. It also involves exclusion from the social area (homeless people live on the margins of society and are detached from that society), and from the legal area (a person without a permanent resident permit cannot, for example, take part in elections or use the healthcare system

Homelessness as a psychological condition is a situation in which persons or families do not have a permanent place of residence that satisfies the minimum conditions in the cultural norms adopted by society. Homelessness in developed countries will be interpreted differently than homelessness in developing countries. For example, in India it is quite common to see people who spend the night on the street go to work the next morning. In such places, this type of homelessness does not necessarily result in social exclusion. In Europe homelessness is a state of loneliness. In most cases, homeless people live alone, without families, sometimes in smaller groups whose common goal is survival. Homelessness is more prevalent in urbanised areas, especially during the colder months of the year. In winter homeless people move to cities, where they have a better chance of finding places to spend the night, such as squats, public places (e.g. train stations) and care and support facilities for homeless people (nights shelters, short-stay shelters, etc.). During the spring and summer months, homeless people migrate from urban areas to rural areas to find seasonal jobs.

Homelessness is a very complex and multi-faceted phenomenon. It is surrounded by legends about the freedom of homeless people, which in fact means that a homeless person who calls himself or herself free is so far detached from society that s/he does not feel that s/he has anything in common with other people, in terms of rights and obligations.

A thorough understanding of the methods used to deal with homelessness is crucial to help us provide proper and responsible support. As homelessness is such a complex phenomenon, there are many different ways to define and explain it.

The Statistics Division of the United Nations' Department of Economic and Social Affairs has defined 'primary homelessness' as persons living without a shelter or living quarters and 'secondary homelessness' as persons with no place of usual residence. In some contexts, homelessness is understood as a lack of access to land as well as to a shelter. In rural Bangladesh, for example, homelessness is assessed on the basis of whether a household has a regularised plot of land as well as a roof overhead. Other definitions focus on being deprived of a certain minimum quality of housing. The Institute of Global Homelessness has proposed the following global definition: 'lacking access to minimally adequate housing', while listing various categories of living situations that fall within this general definition. [17]

One of the most apt definitions was proposed by Prof. Adam Przymenski from Poznan University of Economics in Poland.

'*Homelessness is a situation regarding people or families, who at a certain point of time do not have and cannot provide themselves with a shelter they might consider their* *own and which would fulfil minimum living conditions and would be recognised as a habitable space*. [18]

This definition shows that what is regarded as homelessness in some cultures and countries may not be regarded as homelessness in other cultures and countries. A person living in substandard conditions in countries such as England, the Netherlands or Germany will be recognised as a homeless person, and local authorities will try to support him/her by providing him/her with a better place to live in. In India or Brazil, a person living in a similar situation might not be regarded a homeless person. It is very important to remember that homelessness involves more than just a physical situation.

FEANTSA (the European Federation of National Organisations Working with the Homeless) has developed a typology of homelessness and housing exclusion called ETHOS (European Typology of Homelessness and Housing Exclusion). According to ETHOS, there are two types of homelessness. In the strict sense of the word, people can be both roofless and homeless. However, there are also people in insecure or inadequate housing situations, who are homeless in a broader sense. The definition developed by FEANSTA assumes that there is no single definition of homelessness and the problem is so widespread that it is only possible to try to identify types of homeless persons and to find an the appropriate homelessness measures for type of homeless person and hence the right type of support.

The ETHOS typology begins with the conceptual understanding that there are three domains which constitute a 'home', the absence of which can be taken to delineate homelessness. Having a home can mean three things: having an adequate dwelling (or space) over which a person and his/her family can exercise exclusive possession (physical domain); being able to maintain privacy and enjoy relations (social domain) and having a legal title to occupation (legal domain). From this understanding, the following four concepts follow: Rooflessness, Houselessness, Insecure Housing and Inadequate Housing, all of which can be taken to indicate the absence of a home. ETHOS therefore classifies people who are homeless according to their living or 'home' situation. These conceptual categories are divided into thirteen operational categories that can be used for different policy purposes, such as mapping the problem of homelessness and developing, monitoring and evaluating policies.

Conceptual category		Operational category		Living situation		Generic definition
CONCEPTUAL CATEGORY	ROOFLESS	1	People living rough	1.1	Public space or external space	People living in the streets or public spaces, without a shelter that can be defined as living quarters
		2	People in emergency accommodation	2.1	Night shelter	People with no usual place of residence who make use of overnight shelters or low-threshold shelters
	HOUSELESS	3	People in accommodation for the homeless	3.1	Homeless hostel	People whose period of stay is intended to be short term
				3.2	Temporary accommodation	
				3.3	Transitional supported accommodation	
		4	People in women's shelter	4.1	Women's shelter	Women accommodated due to experience of domestic violence, whose period of stay is intended to be short term
		5	People in accommodation for immigrants	5.1	Temporary accommodation / reception centre	Immigrants at reception centres or in short-term accommodation due to their immigrant status
				5.2	Migrant workers' accommodation	
		6	People due to be released from institutions	6.1	Penal institutions	No housing available prior to release
				6.2	Medical institutions	Stay longer than needed due to lack of housing
				6.3	Children's institutions / homes	No housing identified (e.g by 18th birthday)
		7	People receiving longer-term support (due to homelessness)	7.1	Residential care for older homeless people	Long-stay accommodation with care for formerly homeless people (normally more than one year)
				7.2	Supported accommodation for formerly homeless people	
CONCEPTUAL CATEGORY	INSECURE	8	People living in insecure accommodation	8.1	Temporarily with family/friends	Living in conventional housing that is not their usual place of residence due to lack of housing
				8.2	No legal (sub)tenancy	Occupation of dwelling with no legal tenancy; illegal occupation of a dwelling
				8.3	Illegal occupation of land	Occupation of land without legal rights to do so
		9	People living under threat of eviction	9.1	Legal orders enforced (rented)	Where orders for eviction are operative
				9.2	Re-possession orders (owned)	Where mortgage provider has legal order to repossess the house
		10	People living under threat of violence	10.1	Police-recorded incidents	Where police action is taken to ensure that victims of domestic violence have a safe play to stay
	INADEQUATE		People living in temporary / non-conventional structures	11.1	Mobile homes	Not intended as place of usual residence
				11.2	Non-conventional building	Makeshift shelter, shack or shanty
				11.3	Temporary structure	Semi-permanent structure, hut or cabin
		12	People living in unfit housing	12.1	Occupied dwellings unfit for habitation	Defined as unfit for habitation by national legislation or building regulations
		13	People living in extreme overcrowding conditions	13.1	Highest national norm of overcrowding	Defined as exceeding national density standard for floor-space or useable rooms

Note: 'Short stay' is defined as 'normally less than one year'; 'long stay' is defined as 'more than one year'.
This definition is compatible with Census definitions as recommended by the UNECE/EUROSTAT report (2006)

TABLE 5.1 ETHOS typology of homelessness

The ETHOS typology indicates that homelessness and social exclusion are not only related to people who do not have a dwelling, but also concern housing conditions and threats of eviction. The definition was phrased in order to reflect the fact that homelessness is not a static phenomenon and any definition of it needs to capture the process of housing exclusion and the factors underlining this process.

The process through which people become homeless and the reasons behind it are highly individualised. Therefore, it is impossible to present specific reasons as to why a particular person becomes homeless or remains so. However, certain psychological mechanisms are common, regardless of the person's cultural background or reason for being homeless. The author of this thesis drew up a diagram presenting the various stages of a descent into homelessness and return to society while conducting research on the homeless for his Master's thesis, entitled Architecture for the Excluded: The Structure of Homelessness in the City (see Fig. 5.3). [19] The diagram is based on first-world homelessness, as experienced in Europe and North America, which may be considerably different from the kinds of homelessness experienced in other civilisations and cultural regions. For example, during a discussion in a crisis centre in Jerusalem, Israel, a social worker stated to the author that in traditional societies such as the Jewish or Palestinian societies, the phenomenon of visible homelessness (i.e. roofless and houseless) does not exist. Israel did not have homeless people living rough until after the big influx of Jewish people from Russia in the 1990s. [20]

Like the descent into homelessness, the process by means of which people climb out of homelessness is highly individualised and strongly dependent on many personal factors, including the person's own life history, the reason why s/he became homeless and the way in which s/he became homeless.

The diagram is a simplified scheme that represents a person who has experienced physical, psychological and social homelessness but has managed to leave it all behind him/her.

During the first of the four stages depicted above, a person who has lost his/her home descends into so-called physical homelessness. This commonly occurs as a result of military action or due to a natural disaster, or possibly because of bankruptcy or the breakdown of a family. At this stage, the homelessness is physical, not yet psychological. It is generally linked to a tragedy in which a person has lost a home, without that person actually identifying as a homeless person. During the next stage, the person will start identifying as a homeless person. S/he will experience a sense of exclusion, loss and often loneliness. This is when the homeless person will genuinely be excluded, and will suffer psychological and physical degradation. S/he may now wish to escape from consciousness by taking something that may relieve the pain and the sense of seclusion, such as alcohol, drugs and/or medications. It is at this stage that a homeless person will often become an addict, unless s/he suffered from addiction before.

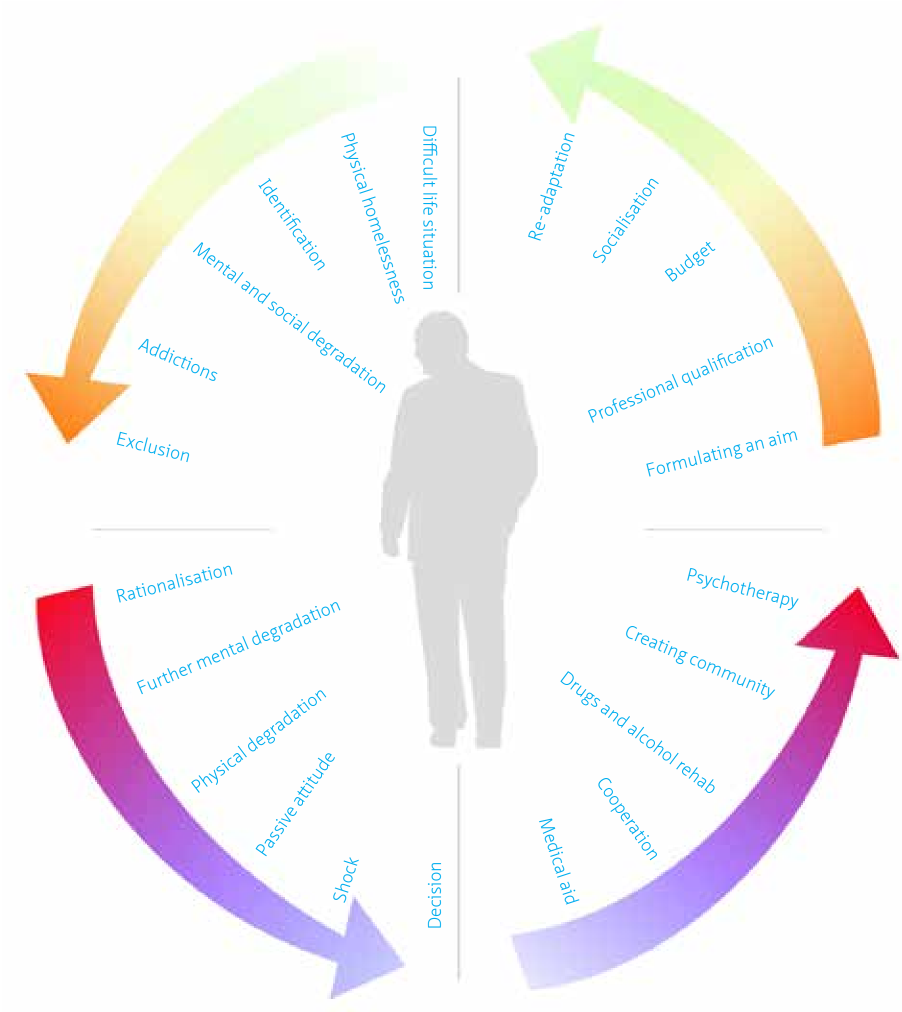

FIGURE 5.3 Theoretical diagram of homelessness

A very important point in the descent into homelessness is so-called 'rationalisation'. This is a psychological mechanism that allows one to accept a bad situation. It is a defence mechanism that makes the situation in which a person finds himself/herself more bearable. When asked a question concerning his/her situation, a homeless person will often reply that s/he may not have his/her own accommodation or resources, but s/he is a free person. Thus is born the awful myth of the homeless person who is supposedly free and independent and homeless by choice. However, it pays to remember the reasons why this person became homeless in the first place. If we do so, we will find that generally speaking, the reasons for a person's homelessness were independent of that particular person, and that this person did not begin to accept homelessness or see its positive aspects until after having been homeless for some time. Rationalisation is dangerous because it reduces a person's willingness to return to 'normal' life, re-socialise and break away from his/her homelessness.

The danger inherent in this stage is that the person will replace the state of being temporarily homeless with the state of permanent homelessness. Once a homeless person starts identifying as a homeless person and starts rationalising his/her position, passivity and indifference will creep in. The result of such a state is learned helplessness, a condition in which the homeless person cannot get out of his/her situation on his/her own, and if s/he gets some temporary relief, e.g. a communal apartment, s/he will not be able to manage it properly. As a result, s/he may lose the accommodation and suffer further degradation.

Deepening homelessness gradually turns into a state of permanent homelessness. It is followed by further psychological degradation and exclusion. Generally, it results in the homeless person's severing his/her relations with his/her family and friends and with people who knew the person before s/he began identifying as a homeless person. Intoxicants, addiction and a lack of personal hygiene due to the person's homelessness will result in the homeless person's becoming paralysed with inertia. Living from hand to mouth, s/he will remain in some kind of haze, in which s/he will feel paradoxically safe because nobody demands anything of him/her. Since s/he does not have any rights or responsibilities, s/he is not far from the truth when s/he says that s/he is a free person. Generally, this state of permanent homelessness lasts until an event occurs that has a considerable impact on the homeless person's life and attitude. It can be a traumatic event or some kind of disease or hypothermia. Often, the turning point in the process of getting out of homelessness is a situation in which a homeless person sustains an injury and, not given a choice, has to ask for help, at the same time giving in to the conditions of hospitalisation or to the rules of a night shelter or a hostel.

The first stage in helping a homeless person who has decided to get out of his/her situation is the provision of medical assistance. Another essential element is a homeless person's willingness to cooperate with social workers, undergo rehab and adapt to the rules of certain social welfare centres. The person's return to the society should begin in small local groups, for example among the occupants of a hostel. Meeting people and sharing duties have a therapeutic effect. It is also essential that homeless people be provided with counselling, during which they will have the opportunity to make rational decisions about themselves and look at their lives with a psychologist's help. This will enable him/her to break away from the aforementioned haze and look beyond it, with a view to returning to society and a so-called 'normal life'. It is vital at this stage that the homeless person have a goal. Goals may include getting a communal apartment, finding a job, helping one's family and/or renewing contact with one's family.

While working on himself/herself in a so-called 'individual programme', the homeless person will learn a trade that will allow him/her to support himself/herself. S/he will learn how to manage his/her finances, time and the like. The job opportunities may occur and give the homeless person the idea that s/he will be able to live independently. Living in a shelter, having gainful employment, not being too financially dependent on others and being able to stay sober all go a long way to helping a homeless person achieve social re-adjustment. The last stage of a successful climb out of homelessness is getting one's own private housing and achieving financial independence.

Needless to say, the diagram showing the steps involved in a descent into and climb out of homelessness is a simplified one. It shows the difficulties and dangers inherent in the slide into homelessness and the tribulations of getting out of this state. Each individual homeless story has his/her own story, and each case will develop in its own way. The various stages or steps noted in the diagram provide a better understanding of what goes on in a person who is sliding into homelessness or a person who is trying to break away from homelessness.

The diagram should be perceived as a means to help one describe the situation and condition of a homeless person, or as a depiction of a process that can be supported by 'soft activities' (psychology, medical or social help) or by 'hardware', such as architecture. For people who take care of people's physical spaces, such as architects, urbanists, planners and politicians, important elements of the above diagram are the crucial points in the process of getting into and out of homelessness such as physical homelessness, rationalization and permanent homelessnes or decision. One of these crucial points is the loss of home – the moment at which a person does not yet regard himself/herself as homeless, but has been deprived of a roof over his/her head. At this stage action should be undertaken as quickly as possible in order to provide such people with some basic conditions that suit their expectations, depending on where they live and what kind of habits they have. Neglecting this stage can result in a deepening of the state of homelessness, with all the associated consequences, which are often irreversible for a human being and costly for society from a sociological and material point of view. Therefore, it is crucial that people who have lost their homes or the places where they live be provided with help at once, so as to prevent them from identifying as homeless people. This may be very difficult, especially in emergency situations such as natural disasters, where in addition to physical losses there is trauma, fear, uncertainty and loss of loved ones. From an architectural point of view, which is mainly concerned with the hardware part of the support to be provided, a safe and relatively comfortable place to live is essential.

There is another important moment in the strategies against homelessness – another turning point, namely the moment at which a homeless person decides to work on himself/herself and tries to break free from homelessness by getting medical care and psychotherapy, getting an education, adapting to having a job, etc. According to the continuum- of-care methodology, which is explained below, these steps should be accompanied by an improvement in the person's physical environment in order to enhance this process. [20]

In western countries, especially in the USA, Australia, Canada, Finland and France, a new system of combatting homelessness called 'Housing First' has become popular in recent years. The idea was conceived in New York in the 2000s and consists in providing homeless persons with apartments as a first step towards re-adjustment and getting out of homelessness. The 'Housing First' method is based on the idea that getting a communal apartment that comes with social services will give a homeless person a stronger base to fight against homelessness and exclusion (see Fig.5.4). A different approach to homelessness is presented in a method called 'continuum of care', which is based on the idea that a homeless person must pass through several stages in order to break free from homelessness. The Continuum of Care programme distinguishes three main stages: prevention, intervention and integration (see Fig. 5.5). In the preventive stage, institutions dealing with the fight against homelessness must prevent people who are at risk from falling into homelessness from doing so by providing them with temporary shelters and financial and psychological support. Temporary apartments for the homeless are an essential part of this stage. The intervention stage includes things such as helping people who sleep rough, placing them in night shelters or hostels with public assistance. Finally, the integration stage consists in stimulating homeless persons' fight against their situation, getting out of homelessness, getting a place in a training apartment, and, ultimately, living in a communal apartment. The two crossing lines on the graph refer to the turning points in the previously described scheme. The first turning point is the moment at which the person becomes homeless, and the second is the moment at which the support given by others or the homeless person's own efforts help him/her break free from his/her homelessness. [20]

FIGURE 5.4 Housing First scheme

FIGURE 5.5 Continuum-of-care scheme

The type of homelessness described above concerns the situation that can be found in the western world, i.e. Europe and North America. However, homelessness is a very broad notion and also includes two other categories: forcibly displaced people and victims of natural disasters.

It is almost impossible to estimate the number of homeless people as some types of homelessness are immeasurable.

The database of OECD countries shows that in 2015 there were 1,777,308 homeless people in OECD countries, including 549,928 homeless people in America. [4] However, these numbers may not concern the broader meaning of homelessness only the persons in assisted accommodations or living rough in urban areas. For example, the official number of homeless people in Poland was 36,161. But this number concerns only those people who receive care from social institutions, while there were another approx. 10,000 people who did not use the care facilities. In the broad sense of the word ‘homelessness’, the number of homeless people in Poland was as high as 300,000-400,000.

The Homeless World Cup Foundation estimates that there were 100 million homeless people in 2005, as well as 1.6 billion people without adequate housing. [21]

Even though the homelessness described above concerns the population of the western world, the mechanisms can be similar in other parts of the world. Moreover, the refugees and immigrants who have come to Europe, will not be granted refugee status and therefore will be excluded from the legal, social and physical domains will likely become homeless (see Fig. 5.6.). It is important to take this consideration into account as the current influx of refugees may result in a growing number of homeless people in the next few years.

FIGURE 5.6 Homeless people sleeping rough in Brussels, 2017

§ 5.3 Design guide for emergency architecture

At present the European Union is dealing with the problem of a growing number of refugees who have fled countries engaged in wars or conflicts. When these refugees first arrive in Europe, be it by boat or by some other route, they are taken to Hotspots or reception centres, where they are registered and identified, and where they are checked for possible links with terrorist organisations. After that, they receive support designed to help them be assimilated into European culture. This support involves lessons in the local language, education, professionalisation and help with national or international legal procedures. Such activities are generally provided at specially designed places where asylum seekers and refugees can live in some comfort and safety, and where they receive support from governmental organisations and aid organisations. It is vital that this process be controlled, and that people are registered at every step along the way. If the process is not controlled, unregistered and unknown people will sneak into the European Union and will be sentenced for illegal residence and taking part in the black economy. Registration and checks are also important to ensure that EU citizens feel safe in their own countries. Integration policies have to be well thought out and cautious to prevent acts of aggression directed at refugees.

The best way to solve the problem is obviously to bring stability to war-torn countries, but in the meantime, hundreds of thousands of refugees need to find a secure place to survive. Developing regions hosted 86% (13.9 million people) of the world's refugees under UNHCR's mandate. This was the highest figure in more than two decades. The least developed countries provided asylum to 4.2 million refugees, i.e. about 28 percent of the global total.

The refugee camps organised by the Red Cross, UNHCR and other aid organisations are places where refugees can find safe place to live. These camps, built in the forcibly displaced peoples' home countries or in a country to which they have fled, must follow certain spatial and organisational guidelines.

The beliefs of the various humanitarian agencies are based on three shared principles: the right to a life with dignity, the right to protection and security, and the right to receive humanitarian assistance. These principles are expressed through the practical actions undertaken by humanitarian organisations. One of these is to provide support and assistance to forcibly displaced people and victims of natural disasters. Everyone has a right to adequate housing, which means: [22]

- Sufficient space and protection from cold, damp, heat, rain, wind or other threats to health, including structural hazards and disease vectors
- The availability of services, facilities, materials and infrastructure
- Affordability, habitability, accessibility, location and cultural appropriateness
- Sustainable access to natural and common resources, drinking water, energy, sanitation and washing facilities, refuse disposal, site drainage and emergency services
- The appropriate settlements and housing with provided safe access to services such as health care, education, childcare, etc.
- Appropriate diversity and cultural identity of housing.

In order to provide adequate housing, organisations must meet these minimum standards.

With regard to the location of the forcibly displaced people, three main groups can be distinguished: urban locations (60%), rural locations, and mixed/unknown locations. It is vital that aid organisations have reliable data on where the refugees are to improve the allocation of resources, the policies and design programmes.

Six main types of accommodation can be distinguished (see Fig. 5.7):

- **Planned/managed camp**
- **Self-settled camp**
- **Collective centre**
- **Reception transit camps**
- **Individual accommodation** (private), which amounted to 67% at the end of 2015
- **Various/unknown**, which by the end of 2015 equalled 2.8 million people under UNHCR's mandate (17%).
  Each of the aforementioned types of accommodation can be location in an urban area or a rural one. In rural locations, most of refugees lived in planned/managed camps in

2016, and only few percent in private accommodation, while in urban locations, 88% of refugees lived in private accommodation and 3.3% in planned camps.

TYPE OF ACO-MODATION	NO. OF REFUGEES			DISTRIBUTION (%)			% URBAN			% WOMEN			% CHILDREN		
	2014	2015	2016	2014	2015	2016	2014	2015	2016	2014	2015	2016	2014	2015	2016
Planned/ managed camps	3,512,500	3,390,900	4,011,000	29.3	25.4	28.6	7.0	1.4	3.3	50.5	51.4	51.4	55.7	57.6	58.6
Self-settled camps	487,500	518,600	525,200	4.1	3.9	3.7	0.4	7.6	7.2	52.9	53.3	52.4	56.3	57.1	56.5
Collective center	302,00	301,900	320,100	2.5	2.3	2.3	95.3	87.1	100	47.8	45.0	18.6	54.4	46.8	17.0
Individual accomodation (private)	7,578,400	8,99,200	8,877,100	63.2	67.0	63.3	87.3	87.8	87.8	47.9	47.5	48.3	47.0	48.2	49.2
Reception/ transit camp	111,700	197,600	8,877,100	0.9	1.5	2.0	15.1	10.7	9.6	51.5	51.3	62.5	51.0	54.3	35.7
Sub-total	11,992,100	13,358,200	14,015,200	100	100	100									
Unknown	3,393,200	2,763,200	3,172,200												
Grand total	14,385,300	16,121,400	17,187,500												

TABLE 5.2 Accommodation of refugees 2014-2016

In general, accommodation in emergency situations comes in the following forms:

- **Dispersed settlements or host families**
- **Mass shelters**
- **Camps (self-settled and planned)**

Dispersed settlements and host families are a type of self-supporting accommodation often occur near by previous accommodation. The homeless person either share the accommodation, or set up a temporary home and share utilities like water, sanitation, cooking facilities, etc. This type of accommodation may occur in both rural and urban areas, and is often found with family members or people of the same ethnic background. The positive aspects of this type of accommodation are quick implementation, a limited need for administrative support, and low costs. Dispersed accommodation fosters self-help and independence and has less of an impact on the local environment than camps. On the other hand, the burden on the hosting families can be significant, both financially and emotionally. Furthermore, it can be hard to tell the homeless persons apart from the host population, especially when registration is needed, and it may be hard to provide a dispersed population with protection, nutrition and health care. Lastly, shelters and other forms of assistance are needed by the host population and the homeless. However, the host communities may receive UNHCR support.

Mass shelters are public buildings and community facilities. In this type of accommodation, homeless persons are accommodated in pre-existing facilities such as schools, barracks, hostels, gymnasiums or warehouses. Usually this type of accommodation is found in urban areas and it is considered transit accommodation, i.e. temporary accommodation. Such buildings can be made available immediately and services such as water and sanitation are generally available. However, such types of accommodation may quickly become overcrowded and/or be damaged. Moreover, the buildings cannot be used for their original purposes by the local community while the refugees are staying in them, and the people staying in them lack privacy.

Spontaneous, self-settled camps should be avoided to the maximum extent possible. Since they are formed without adequate planning, there is a risk of their becoming an unfriendly environment with overly costly services, a lack of supplies, inadequate shelter, overcrowding, and possibly conflicts with the local community. For this reason, such camps may have to be re-designed and relocated. However, sometimes a self-settled camp may be the only option in an emergency situation.

Planned camps are a type of accommodation built for a particular purpose, where sufficient services can be provided to a large population in a centralised manner. The support provided by volunteers in planned camps is more effective and more easily organised and specifically targeted at homeless persons. Camps pose certain threats, such as a high risk of the spread of diseases and health problems, especially in highly populated camps. Furthermore, camps may cause environmental damage. Lastly, registration may be problematic in large camps, and it may be hard to distinguish between actual inhabitants and other persons, who can often stay in camps without being noticed.

It is essential for the safety and well-being of homeless that the site of the camp be well chosen, the camp is well planned and the shelters be built in accordance with specific criteria. Decisions about site selection, planning and what type of shelter to provide should be made by means of an integrated approach incorporating the advice of a specialist and the views of future inhabitants.

§ 5.3.1 Site selection

The site should be selected, and the camp planned out, prior to the arrival of homeless persons, although allowance should be made for changes at a later date. Unforeseen events may require that a site planned beforehand be adapted to the new circumstances. The choice of a site should take into account criteria related to the potential beneficiaries (number, types or categories), location (distance from major towns, distance from the border, security and protection, local health and other risks, distance from protected environmental areas), basic characteristics (area, possibility of expansion, land use and rights, topography, elevation, soil condition, water availability, drainage, chances of installing sanitation facilities and water supply, climatic conditions, vegetation and other environmental conditions), complementary and supportive services (nearby villages and communities, accessibility, proximity to health and education services, distance to electricity source, proximity to economic centres, agriculture, possibility of harvesting the woods for wood to be used in construction or as fuel).

The most important ones of these criteria are the following:

- Water supply – the availability of an adequate amount of water is the most important criterion. It is also the most problematic one.
- Size of the site – the recommended minimum area of the camp is **45m^2 per person**. The minimum area **should not be smaller than 30m^2 per person, excluding agricultural land.** The area per person includes all communal services and services such as roads, paths, education, sanitation, water, storage, markets, etc.
- The number of people in a camp should not exceed 20,000. Smaller camps holding just 500-2000 persons are advisable. The camps should have the potential for expansion. The population of a camp can grow as fast as 3-4 % per year due to the ratio of deaths to births.
- Land use and rights – it is important to identify who owns the land, as UNHCR does not buy or rent land. Camps must be located on public land provided by the government. The people living in the camp must be granted the right to use the land and exploit it by harvesting wood, breeding animals and cultivating land.
- Topography, drainage and soil conditions. The site should be located above flood-prone areas. The optimal slope of the site is between 1 and 5%. The slope should

not be steeper than 10% due to the need for levelling and costly additional work. However, completely flat sites may pose a problem in terms of drainage of wastewater and rainwater. It is important from a sanitary point of view that water be absorbed by soil. Pit latrines may or may not be able to be used, depending on the type of soil. The groundwater level should be at least 3m below the surface of the site.

- Accessibility – the site must be accessible and located at a reasonable distance from sources of supplies such as food, cooking utensils, fuel and materials used for shelters.

- Climatic conditions, local health and other risks – the chosen site should be safe and free of major environmental health hazards and natural disasters. Strong winds may damage the shelters, but a slight breeze is advisable for better camp ventilation. It is vital that year-round weather and temperatures be considered.

- Vegetation – damage to the topsoil during the pre-operational work on the site must be avoided at all costs. The quality of the soil, and cultivation potential is an important matter. The site should be checked for the availability of vegetation and biomass for heating purposes. Camps should not be located near ecologically and environmentally protected areas.

The site should be chosen with the assistance of experts from local governments, UNHCR's Technical Support Section, NGOs, local industries, engineering faculties and professional organisations. Important fields that may require expertise include hydrology, surveying, physical planning, engineering, public health, environment and social anthropology. The latter is important in order to create the kind of conditions in the camp that the refugees are used to in their place of origin.

Even if there are not enough resources for services such as education, recreation, playgrounds and other social infrastructure and communal areas when construction of the camp first begins, space must be reserved for such services, as they have a major influence on the human environment.

§ 5.4 Site planning

Site planning should be guided by the principle of a decentralised community-based approach, where families, communities or other social groups constitute the spatial arrangement. This means that planners should use the 'bottom-up' approach where the needs and characteristics of the families are considered first, and where the arrangements made reflect the wishes of the community. Future users of the site should be involved in the site planning process. Each community should possess its own services, such as latrines, showers, water supply, cooking areas, rubbish collection and places where clothes can be washed (see Fig.5.7). This enhances ownership and therefore leads to better use and maintenance of such facilities. Individual communities should not have closed-off sections. Camp sections should be kept open so as to allow better control and greater interaction with other communities.

Camps should be organised as follows:

MODULE	CONSISTING OF	APPROX. NUMBER OF PERSONS
1 family	1 family	4 -10 persons
1 community	16 families	80- 100 persons
1 block	16 communities	1,250 persons
1 sector	4 blocks	5,000 persons
1 site (camp module)	4 sectors	20,000 persons

TABLE 5.3 Modules of the camp

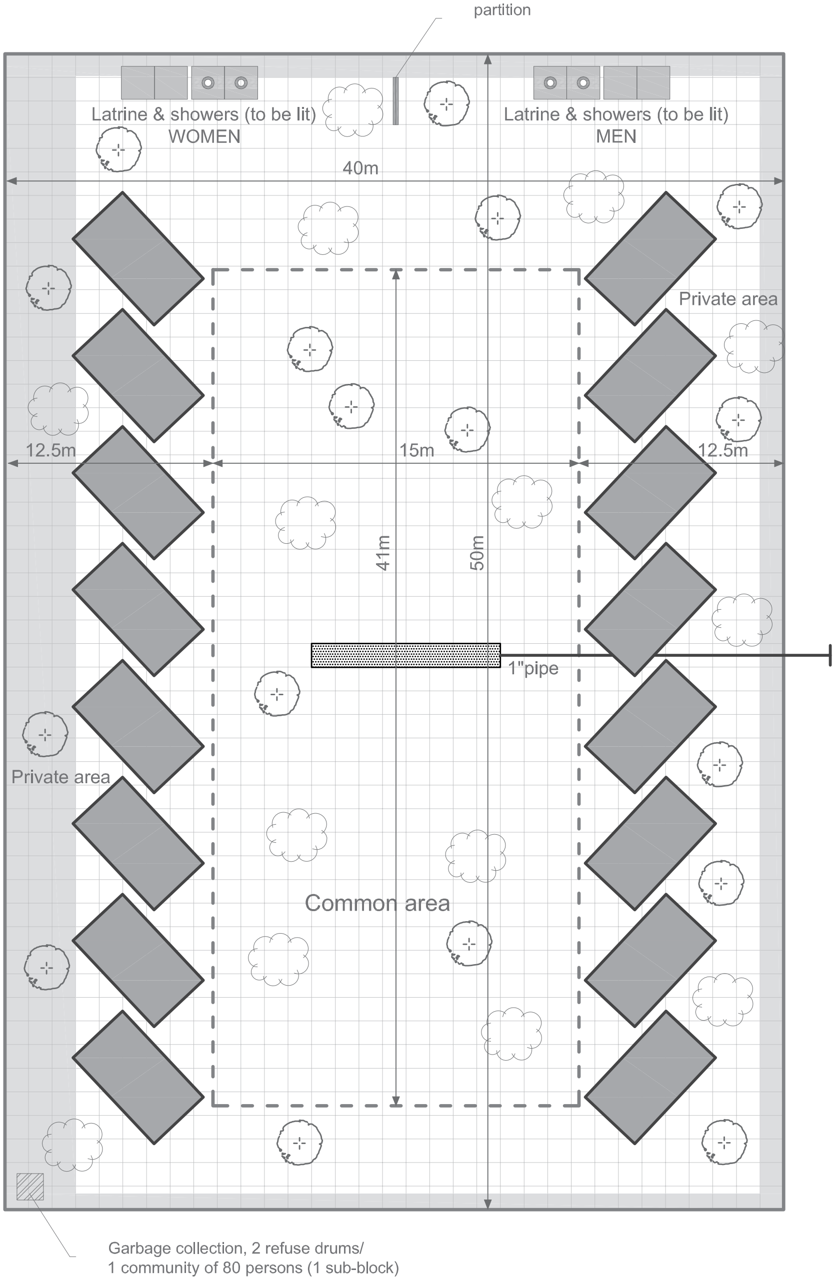

FIGURE 5.7 Sub-block – community area in a refugee camp plan

§ 5.4.1 Master plan

The master plan of a camp should consider both natural and planned features, such as rivers, hills, flood plains, swamps, rocky patches, existing buildings, roads, bridges, farmland, electrical power grids, water pipelines, drainage systems, environmental sanitation plan, water distribution, utilities, lighting, administration areas, educational and health facilities, warehouses, distribution centres, nutrition centres, community centres, playgrounds, sport facilities, religious places, markets and recreation areas, fire prevention breaks and agricultural plots. The master plan should be prepared in accordance with the following standards:

1 WATER TAP	PER	1 COMMUNITY (80-100 PERSONS)
1 latrine	Per	1 family (4-10 persons)
1 health centre	Per	1 site (20,000 persons)
1 referral hospital	Per	10 sites (200,000 persons)
1 school	Per	1 sector (5,000 persons)
4 distribution points	Per	1 site (20,000 persons)
1 market	Per	1 site (20,000 persons)
1 nutrition centre	Per	1 site (20,000 persons)
2 refuse drums	per	1 community (80-100 persons)

TABLE 5.4 Standards for camp's masterplan

The layout described in the master plan depends on the conditions encountered in the physical terrain as well as on the size of the camp, its connection to available infrastructure and local roads, distance from the nearest urbanised area and surroundings. Basically, camps are designed on a rigid grid, in which streets cross each other at right angles, thus dividing the camp into sectors and blocks. However, other arrangements are possible (see Fig. 5.8). [24]

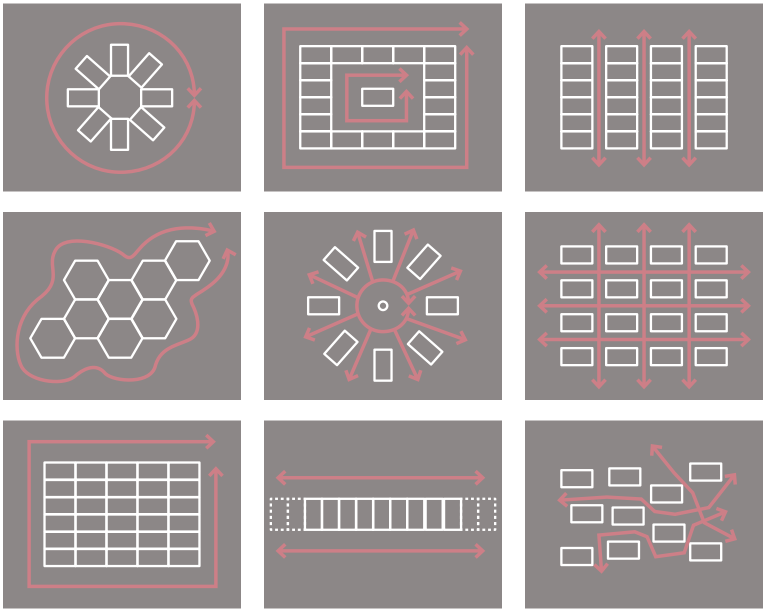

FIGURE 5.8 Types of emergency camps

§ 5.4.2 Modular planning

As mentioned before, planners should take the bottom-up approach, which means that the family must be the starting point for the spatial planning of the camp. The first thing that should be considered is the needs of a single family: distance to supplies (water, latrines), relationship with other community members, housing traditions and the spatial arrangements of the shelters. Then a layout should be drawn up for a community, and after that the larger issue of the overall layout of the camp can be considered. This way of modular planning allows camp organisers to consider the needs and demands of smaller groups and adjust their planning and the location of the individual communities in such a way that individuals and families will be able to create communities and support each other.

The layout of the camp should enhance neighbourly relations and community interaction. Furthermore, it should provide clearly identified functional areas, such as supplies (latrines and water supply), markets and both public and semi-public places.

The layout should encourage people to look after places and services, so that they will be better maintained. Rigid grid layouts often prevent functional areas in a camp from being properly arranged. However, this type of layout is often used because of its simplicity and the speed with which it can be implemented. The layout of the site should be based on such factors as family structures, cultural backgrounds and social groups.

It is very important that the environmental impact of the camp and the ecological burdens that can be created in time be thoroughly considered. Shelters must be suited to the local climate. They should not be constructed with local wood, so as to protect the region's environment. The ecological burden of a camp may also be reduced by means of proper insulation and passive energy systems.

§ 5.4.3 Services and infrastructure

As a source of water is a major requirement for a camp location, latrines and sanitation points dictate the layout of the site. A high population density and poor sanitation can easily cause health problems, including epidemics. Uncontrolled defecation and public latrines should be avoided. However, if public latrines are the only possible option, they should be positioned in such a way that they will be accessible from the road and will have enough space around for maintenance. Ideally, each latrine will be dedicated to one family (four to ten persons), as this will encourage people to keep their latrines clean, which is good for long-term hygiene. The ideal location for a latrine is on the family plot, but as far as possible from the shelter. If this solution is not feasible, the latrine should be installed in a community area that is home to a few families or groups. Ideally, it will not serve more than twenty persons. The water supply point should be located no more than 100 metres from the shelter. The layout of the camp should feature a water distribution grid with water pipes below the ground (40-60cm below the surface, or 60-90cm if the camp is located in a country with low temperatures). If a water distribution point serves a full community (80-100 persons), far less water will be wasted. Grey water can be used for the irrigation of gardens.

A site should be equipped with a network of roads and pathways. The main roads should be built above flood level and should be accessible all year round. For safety reasons, a distance of 5-7 metres should be observed between the edge of the main road and the border of the plots.

In every 300m of built-up area there should be an empty space 30m wide that serves as a firebreak. Such firebreaks should serve as divisions between blocks (16 communities, 1,250 persons). The empty spaces can be used for recreational purposes or for cultivation of fruit and vegetables. The distance between separate buildings should prevent a collapsing or burning building from touching its neighbour. The distance between the buildings should equal twice their height. If highly flammable building materials are used, the distance between the buildings should be three or four times their height. The direction of the prevailing wind plays an important role in fires, so this should be taken into account during the camp planning.

The administrative and communal buildings should be located in places where they will serve the greatest number of people. They should be designed in a flexible and universal way that will allow them to be used to host different activities and functions at different times. They may provide centralised facilities and services to larger groups, such as site administration, initial registration and health screening, health care, food and water supply, education, storage, therapy, market places, community centres, etc. Other services and facilities should be more decentralised and serve smaller groups: water points, latrines, bathing and washing areas, rubbish collection, supplementary feeding centres, education facilities, commodity distribution centres, etc. Depending on the size of the camp, the centralised services building can be located at the heart of the camp or at the entrance to the site.

§ 5.4.4 Camps' spatial needs

Minimum standards are evaluated by a professional and are based on UNHCR's Emergency Handbook [23] and Humanitarian Charter and Minimum Standards in Disaster Response Sphere. [22] However, often the camps get overcrowded in time. As a result, the inhabitants lose their dignity and the space they require to pursue their livelihoods. As mentioned before, many refugee camps are full of inhabitants who have been there for a long time, often for more than twenty years. The average lifespan of a refugee camp is close to seven years. Therefore, when planning a camp, the long-term perspective has to be taken into account. The annual population growth rate in camps is 3-4%, which means that in a camp of 20,000 displaced people, the population will grow to 29,605 within nine years, which is just two years more than the average lifespan of a camp. If the average land area per person in the camp follows the guideline of 45m^2 per person, by the end of the ninth year this area per person will have been reduced to 32m^2, which is below the acceptable minimum. Moreover, in the guidelines no area is assigned to workshops, home-based enterprises, granaries or tool storage, nor are there any numeric guidelines for non-residential buildings such as schools, clinics, warehouses, administration offices or community centres. Jim Kennedy (2005) suggests that camps be planned as a hierarchy of different interlocking spaces, of which some are absolutely private, some absolutely public, and many are a combination of the two. [25] Therefore, the physical structures should help form a flexible and adjustable plan, which will follow the growing population and changing needs of the residents. Kennedy states that an extra 100-150% land is necessary, not for the initial buildings but for low-intensity use, perhaps for several years. [25]

If we look at the duration of the period during which people who have lost their houses (particularly refugees) stay in refugee camps, it will become clear that we should regard them not as refugee camps but rather as refugee cities. As Kilian Kleinschmidt, one of the world's leading authorities on humanitarian aid, says: *In the Middle East, we were building camps: storage facilities for people. But the refugees were building a city. These are the cities of tomorrow. The average stay today in a camp is 17 years. That's a generation. Let's look at these places as cities*. [26]

The organisers of the camps should take into account the way people will lead their life in the camps in the future with a normal daily routine. This problem was addressed in the thesis with which Twana Gul graduated from TU Delft's Faculty of Architecture and the Built Environment. Gul, who visited several refugee camps in northern Syria, proposes in his thesis that camps be treated as cities, with all that entails:

Basically, the bare camps are not performing as emergency camps anymore, but more as cities. When time passes by – for instance, one to two years – people try to pick up their lives again and try to survive the poor conditions with the use of their occupation. Let's say, one of the refugees was in "his previous life" a barber in the city centre of Singal, after his settlement in the camp he becomes conscious of his stay. He will not return in the coming weeks, but probably after six months, a year or two. Therefore the formal barber would like to establish a barbershop in the camp to enhance the conditions for his family. However, the camp has not been designed to embrace such an idea and if the camp has attempted to define a main street with little shops, this particular individual does not live in that area. Nevertheless, he erects the shop next to his shelter. With more people in the same circumstance, the shops and services are shattered within the transforming camp and reduce the economic rate of the booming city. [24]

The camps should be considered 'interchange stations' where refugees and victims of disasters are secure and receive some preparation for a self-sufficient life in the future, no matter where that future takes place – in their home country or in a foreign country. However, in many cases, such camps turn into refugee cities where people continue to live for decades.

The other types of camps are reception and transit camps, also called Hotspots. Such camps are temporary places of refuge for refugees who have only just arrived from their own countries (before they are moved to other, more suitable and better-prepared camps) or who are about to be repatriated. Such camps are designed for a short stay of between two and five days. Reception and transit camps are characterised by a high turnover rate. The primary criteria for planning this type of camp are good access, availability of water, good drainage and a terrain with a slope of 2-5 percent, sanitation units that satisfy all the requirements and a strategic location. Reception and transit camps are also characterised by a permanent infrastructure and operational maintenance, for example with regard to disinfection. Since the residents are only expected to stay for a short period of time, the minimum space required is 3.0m^2 per person. Such camps often provide mass accommodation in the form of barracks or big tents. A room with an area of 85m^2 may serve 14 to 25 persons who will only be staying for a few days. However, in rooms of that size, partitions are advisable between every group of five persons, to give families some privacy. Sanitation units, too, can serve more people than in other, more permanent camps, namely twenty persons per latrine and fifty persons per shower. Other important standards to be met are food preparation zones (100m^2 per 500 persons), storage (150-200m^2 per 1000 persons), arrival/departure zones that are separate from the accommodation zones, and separate accommodation for persons held in quarantine. Public buildings can be used for these types of activities, too.

For effective interventions, close coordination and cooperation with other sectors are required. For example, it is necessary that adequate water and sanitation facilities be provided in the area where the shelters are deployed to ensure the health and dignity of the affected people.

§ 5.4.5 Modular, Circular Model Camp – MCMC

The Modular, Circular Model Camp for the refugees was designed by the author of this thesis as example of a layout that includes the aforementioned indicators and values.

The camp with a circular layout, was designed for one thousand inhabitants. The camp was created as a model example, without any specific context. The only information provided was the location of the camp, which was in Lebanon. Therefore topography and land ownership were not an issue. It was assumed that the planned camp would have access to water.

The area of the camp is 75,500m². The camp has a circular plan with a 310-metre diameter. One thousand persons are expected to live in the camp, mostly refugees from Syria. This amounts to 75.5m² per person, which is 66% more than the minimum standards (45m²/ person). Since the camp may grow and turn into a city, space must be reserved for expansion. The circular plan allows the camp to grow proportionally towards the outer rim, by creating additional rings. However, the number of inhabitants should not exceed 2,000.

A bottom-up approach is adopted, which means that the community level is the basic social unit of the camp. There are twenty communities, each consisting of eight shelters, i.e. 30-40 inhabitants. Each community possesses its own services, such as latrines, water supply and a cooking area. The shelters are installed at a sufficient distance from each other (four to five metres), meaning that further expansion is possible. Each community plot is divided into a semi-private space for daily activities and private parts, which surround the shelters. Six communities form a quarter (see Fig. 5.11). There are five housing quarters, with 240 inhabitants each (see Fig. 5.9). A sixth quarter is dedicated to services (nutrition, health care, education, culture) and infrastructure (warehouses, workshops).

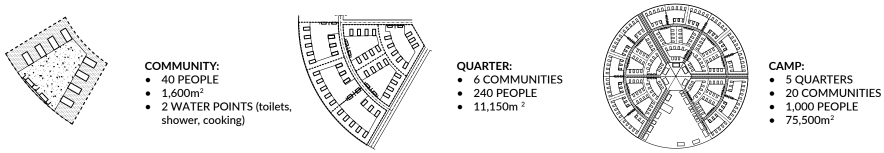

FIGURE 5.9 Community, quarter and camp relations

The master plan for the camp involves a circle divided into six quarters (see Fig.5.10). These are separated by roads. There are two types of roads: roadways, which stop at the outer perimeter of the camp, and secondary roads, which can be used by pedestrians and are also used to provide water to the communities. In the middle of the camp, there is a central square with utility buildings, which in time can transform into local market supporting the growth of the economy. The uninhabited area of one-sixth of the camp is reserved for public buildings and public spaces, and for potential entrepreneurs and businesses. This area is dedicated to all the activities the camp needs to operate smoothly, such as nutrition centres, distribution points, health care and education. In time, the place will be able to host activities such as education, sport, recreation, production and trade, as well as public services.

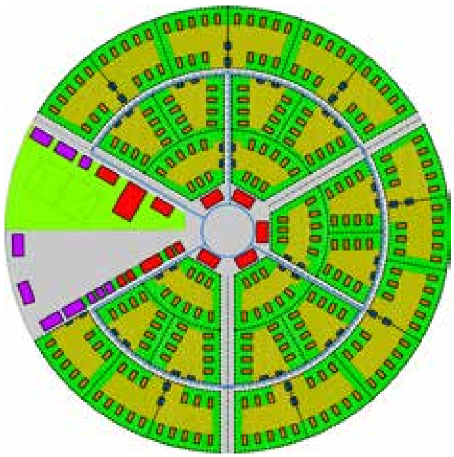

FIGURE 5.10 Modular Circular Model Camp master plan

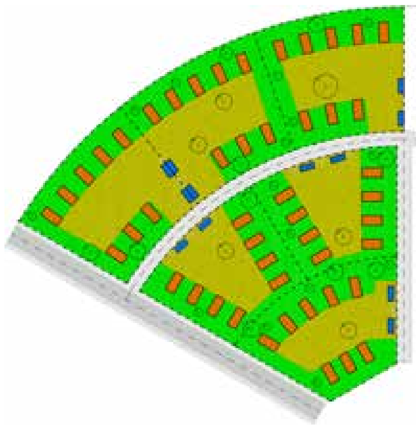

FIGURE 5.11 MCMC quarter plan

LEGEND:
- PRIVATE / GREEN
- SEMI-PRIVATE, COMMUNAL
- PUBLIC AREA
- FOOTPATH
- STREET
- WATER SUPPLY
- WATER POINTS (toilets, showers, cooking)
- HOUSING
- SERVICES (nutrition, health care, schools, social, culture, religion, re-tail, camp management)
- TECHNICAL (workshops, warehouses, infrastructure)

The design of the MCMC is based on the indicators and standards provided by aid organisations and professionals. The camp has a circular plan. However, in reality, the terrain and topography of the place, as well as its connections to existing infrastructure (i.e., roads), may significantly affect the model layout. What is important about the plan is the spatial relation between the community areas, their sizes and the camp's potential for growth and development.

The circular master plan, which is reminiscent of the ideal cities of the sixteenth century, such as Palmanova, or of the nineteenth-century idea of garden cities first proposed by Ebenezer Howard, allows planners to keep a dense and compact layout with minimal distances and easy control.

§ 5.5 Shelter

Everyone has a right to adequate housing. This includes the right to live in security, peace and dignity, with legal protection for tenants, as well as protection from forced eviction and the right to restitution. [22] Shelters are hugely important in camps, being the places where people who have lost their homes or have been forced to leave them can find safety, privacy and relief from their traumas. Losing one's house is one of the most important factors contributing to primary stress. The right kind of shelter brings protection against climatic conditions and serves as a transitional home, where people have their belongings, space to live and emotional security. It should be suitable for different seasons and should also be culturally and socially appropriate.

The type of shelter and the type of settlement is determined by the type and scale of the disaster and the extent to which the population is displaced.

There are four different types of relief accommodation, which can be used by victims of human-made and natural disasters and the homeless (see Fig. 5.12): [27]

- **Emergency shelter** – a place where survivors stay for a short period of time during the height of an emergency. This can be in a friend or relative's house, public shelter or public place.
- **Temporary shelter** – used for a stay that is expected to be short, ideally no more than a few weeks. The shelter may be a tent or a mass shelter shared by many people.
- **Temporary housing** – a place where victims or homeless people can reside temporarily for a period ranging from six months to several years. They can learn to return to their normal daily activities (if they are victims of natural or human-made disasters) or re-adapt to society (if they are homeless people). The house may be prefabricated, or alternatively, it may be a rented house or apartment.
- **Permanent housing** – the rebuilt house to which the victim returns, or a new house in which the victim will be resettled and live permanently.

The first three types are referred to as **temporary accommodation.**

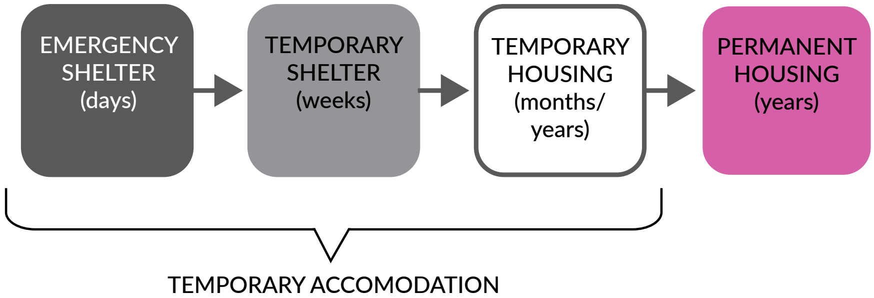

FIGURE 5.12 Shelter typology

The term 'shelter' refers to a place to stay during the period immediately after the disaster that has suspended the victim's daily activities. The term 'housing' involves a return to household responsibilities and a daily routine.

The typology proposed by the International Federation of Red Cross and Red Crescent Societies divides post-disaster (natural and human-made) shelters into the following categories (see Fig. 5.13): [28]

- **Emergency shelter** – a short-term shelter that provides life-saving support, the most basic shelter that can be provided immediately after a disaster.
- **Temporary shelter** – a post-disaster household shelter designed as a rapid shelter solution. The lifetime of the shelter may be limited due to the fact that rapid and low-cost construction must be prioritised.
- **Transitional shelter** – a rapid post-disaster household shelter made from materials that can be upgraded or re-used in more permanent structures, or that can be relocated from temporary sites to permanent locations or be recycled. They are designed to facilitate affected people's transition to a more durable form of shelter.
- **Progressive shelter** – a post-disaster household shelter planned and designed to be upgraded to a more permanent shelter at a later stage. This can be achieved by further integrating transformation and alteration possibilities into the structural basis of the unit.
- **Core shelter**/One-room shelter – a post-disaster household shelter planned and designed as a permanent dwelling. Core shelters allow future expansion of the shelter by the inhabitants, thus turning it into permanent accommodation.Core shelters allow

facilitating and future process of extension by the household in order to end up as a permanent accommodation. The purpose of a core shelter is to create a one-or-two-room home that provides safe post-disaster shelter that reaches permanent housing standards and facilitates development. This type of shelter is mainly used in areas stricken by natural disaster, as forcibly displaced people aim to return to their home countries.

Temporary shelters and transitional shelters are often called '**T-shelters**'.

The various types of shelters overlap, as sheltering is a process rather than a product. Phrases such as 'transitional shelter', 'progressive shelter' or 'core shelter' relate to an approach rather than a phase of response. The design of a shelter cannot be transitional or progressive on its own. What is critical is the context in which the shelter is built.

The terminology used is influenced by a mixture of contextual factors. They range from the level of permanence expected of the shelters and the materials from which they are made, the site on which they are built and local politics.

Emergency shelters are usually provided in the aftermath of a disaster.

T-shelters are designed for a limited lifespan and are intended to be relocated, re-used or recycled.

Progressive shelters and core shelters are built on permanent sites with the goal of becoming part of a permanent solution. This solution is applicable in the event of a natural disaster, as the people affected by the disaster do not have to leave their own country.

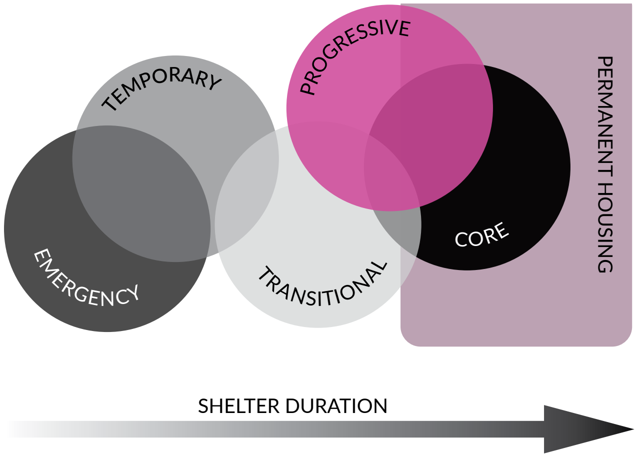

FIGURE 5.13 Types of shelters according to the IFRC, adopted from [28]

It is highly advisable that future inhabitants take part in the process of constructing their own houses, as this will reduce costs and promote a sense of ownership and self-resilience.

An individual family shelter is always better than communal accommodation, as it provides psychological comfort, privacy and emotional safety, and supports the reunification of families after all the traumas they have suffered. A shelter should be made out of fireproof material, especially when heaters are used inside the shelter. Minimal equipment like blankets, mattresses, heaters and extra plastic sheets should also be provided.

The most proper set-up and materials for shelters are those with which their future users are familiar because they used them in their places of origin. Prefabricated or special emergency shelters often do not prove to be a practical solution, either costs-wise or with regard to the users' cultural background. However, in urgent situations, the use of prefabricated shelters is advisable. The most common solution is family tents. The biggest problem with this is that tents which are intended to be used for no more than six months end up becoming permanent accommodation. This kind of accommodation lacks basic features such as security, thermal insulation and privacy, and therefore leaves refugees in an insecure situation.

The most desirable solution is a shelter made of local material, which is easy to construct and labour-intensive. However, the use of local materials and resources like wood, soil, plants, etc. can damage the local environment. Ideally, the material used for a shelter would be environmentally friendly.

he minimum standards for the size of a shelter are: [22, 23]

- **Minimum area of 3.5m² per person in warm, tropical climates**. This area does not include cooking spaces, which can be organised outside.

- **Minimum area of 4.5 to 5.5m² per person in colder climates or urban situations**, where the cooking and bathing facilities are inside the shelter.

The structure of the shelter should allow modifications and flexible arrangements. It is worth keeping in mind that in cold climates, most of the daily activities will take place inside the shelter.

As mentioned before, prefabricated shelters or buildings often do not prove efficient, even if they have proper thermal insulation. The main reasons why they are not efficient are as follows:

- The shelters require long and costly production and shipping
- The shelters must be assembled
- The shelters get hot in hot climates
- The shelters may not satisfy cultural and social norms
  The shelters should be manufactured in advance and prepared for transportation.

Shelters to be used in regions with low temperatures, snow and rain in which wintery conditions may last for three to five months at a time must meet the following criteria:

- Structural stability
- The components and parts of the shelter (walls, roofs, windows, doors) must be protected against the wind
- Parts of the shelter must be insulated
- Kitchens and sanitary units must be protected and heated
- The indoor temperature should be at least 15°-19°C
- A 5-7 kW heating stove should suffice to heat a space with an area of 40 to 70 square metres. The heating stove should also be able to be used as a cooking facility.

Sheltering as a process requires the appropriate approach to a whole range of factors that are crucial for the humanitarian response. Shelter as a physical object is just the hardware part of the whole range of support, which also includes water supply, nutrition, sanitation and psychological and physiological health care that ensures the health and dignity of people whose lives have been upended. However, this hardware is essential for the well-being of people in extremely difficult situations, in that it provides them with the protective conditions they need to live in security, comfort and privacy.

§ 5.5.1 Function-oriented design for emergency and relief architecture

The pyramid of needs created by the American psychologist Abraham Maslow in 1943 helps us understand the hierarchy of human needs. Despite the fact that the pyramid is a simplification and some exceptions have to be taken into account, it helps us understand more clearly what the areas of needs are. As Maslow argues in his book Motivation and Personality, 'At once other (and higher) needs emerge, and these, rather than physiological hungers, dominate the organism. And when these in turn are satisfied, again new (and still higher) needs emerge, and so on. As one desire is satisfied, another pops up to take its place.' [29]

People who cannot satisfy their first, primary needs will not be able to satisfy other, higher needs, either. The pyramid depicts from the bottom to the top what the essential needs of living creatures are and how they can be managed by humans.

The first level comprises needs common to all living creatures. They are called physiological needs – things such as breathing, food, water, sex, sleep, homeostasis and excretion, which are basic conditions to survive. These physical needs do not motivate people once they have been satisfied.

The next level comprises needs that operate on a psychological level: safety-related needs. People need to experience physical security and have secure employment, resources, morality, a family, good health and property.

These first two layers of needs are vital from the emergency architecture point of view. Basic needs can be satisfied, and once they have been satisfied, they disappear. Basic needs determine whether or not there is room for higher needs, which are represented by the next three levels of Maslov's pyramid.

The need for love and a sense of belonging make up the third level of needs. They emerge once a person's physiological and safety needs have been satisfied. As Maslow put it, giving love means that a man who attains this level will *feel kindled, as never before, by the absence of friends, or a sweetheart, or a wife, or children*. [30] Similarly to the primary needs, the need for love and a sense of belonging is only felt when a person experiences a lack of love and belonging.

The conceptual model of human-centred design created by Zhang and Dong (2009) shows that Maslow's pyramid of needs is parallel to design evolution (see Fig.5.14). According to Zhang and Dong, physiological and safety needs can be fulfilled by function-focused useful design. Esteem and social needs can be satisfied by usable, consumer-focused design, while self-actualisation needs can be satisfied by desirable (or pleasurable) human-focused design. [31]

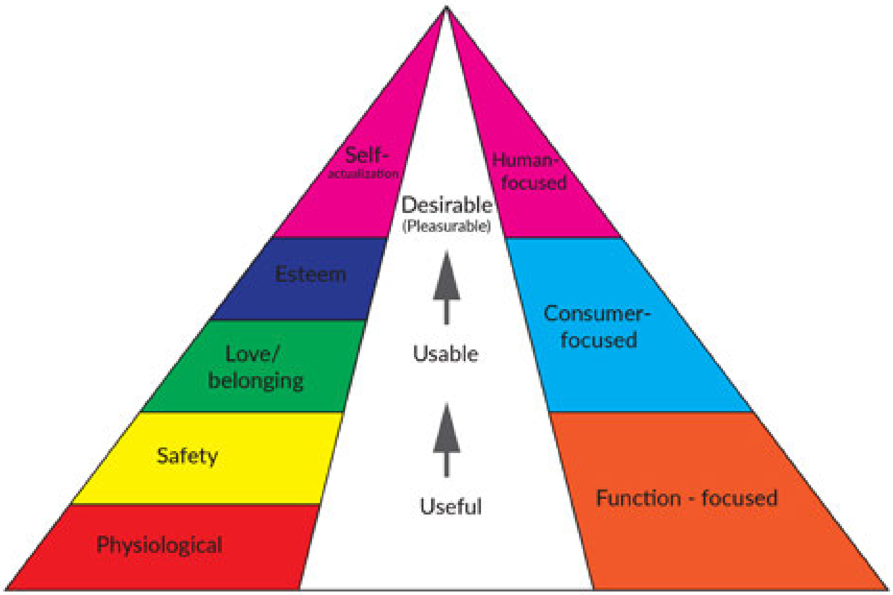

FIGURE 5.14 Pyramid of needs and design evolution, adopted from [31]

It seems obvious that emergency shelters represent function-focused design, which is useful and fulfils the physiological and safety needs. However, it is important to see the broader perspective in relief architecture. After providing the necessary shelters that satisfy minimum living conditions, camp planners should consider the next step, and upgrading of the shelter, and the design of the whole plot of the emergency camp, should be taken into account from the beginning of the whole aid process.

This argument shows that the provision of temporary shelters – actual houses with solid walls and roofs instead of tents – may have a significant impact on the development of the persons temporarily living in emergency or refugee camps. The tents provided by UNHCR barely fulfil physiological needs and often do not meet the requirements to satisfy the safety needs, either. Take, for example, the tents provided to the refugee camps in Iraq. During the winter of 2014 and 2015 many of these tents collapsed because of the heavy snow that had fallen on them. New solutions should be adopted that ensure better thermal comfort, with rigid walls that will give refugees a feeling of safety as well as of privacy. Comfortable houses would also go a long way towards fulfilling the need for love by giving to the family their own space.

§ 5.6 Emergency shelters

Emergency and relief architecture can be manufactured out of paper elements and components. The projects presented below are categorised by type of shelter, depending on the duration of the time during which the shelters will be used (emergency shelter – emergency housing – temporary housing – permanent housing) and hence their complexity.

§ 5.6.1 Paper Partition Systems nos. 1-4

After the Niigata earthquake of 2004, people affected by the earthquake were forced to evacuate to gyms and large buildings with high ceilings, where they had no privacy. This was a source of much distress. To alleviate this distress, Shigeru Ban and his students from Keio University proposed Paper Partition System no. 1 (PPS 1), a simple paper structure to be erected inside the evacuation site to give people some privacy (see Fig. 5.15). Paper honeycomb boards were used for flooring and walls, and the roof structure was made out of square paper tubes. The dimensions of the structures allowed them to be transported by minivan, and the joints and assembly process were designed in such a way as to make construction easy for refugees without specialist knowledge. PPS_1

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was designed for family use. However, the prototype was mainly used for studying, games, a clinic for the elderly and breast-feeding babies. [32]


FIGURE 5.15 Paper Partition System no. 1


FIGURE 5.16 Paper Partition System no. 2

One year later, after the Fukuoka earthquake, Ban proposed Paper Partition System no. 2, in which honeycomb panels were used only as partition walls, with an approximate height of one metre (see Fig. 5.16). This change was implemented due to a need for overview and control of overcrowded places. PPS 1 did not allow that, thus creating a situation with a potential for violence. Paper Partition System no. 3 is an improved version of PPS 1 and PPS 2, in which white fabric curtains are hung from a frame made of paper tubes (see Fig. 5.17). This third version was lighter and cheaper and could be assembled by any volunteer. It provided full-height partitioning that gave families some privacy. In PPS 3 the connections between the paper tubes are wooden prefabricated elements. This solution was changed in PPS 4, in which paper tubes were inserted into each other, which resulted in an even cheaper solution, as well as faster assembly (see Fig.5.18). [32]


FIGURE 5.17 Paper Partition System no. 3


FIGURE 5.18 Paper Partition System no. 4

§ 5.6.2 Cardborigami

Cardborigami is a simple shelter developed by Tina Hovespian during her studies at the School of Architecture of the University of South Carolina. The designer was inspired by origami folding techniques, which she decided to use on a bigger scale to create a tunnel-like shelter for homeless people in the United States and victims of natural disasters (see Fig.5.19). Hovespian's pop-up shelter can be folded flat, which is handy. Homeless people can take it with them after spending a night in it. The shelter can be erected by simply unfolding the C-shaped flat package, which will create a tunnel that can host two people. Cardborigami provides users with a very basic shelter – basically, just a roof over their heads. It is made of corrugated cardboard, which is waterproof and flame retardant. As Hovespian has said in interviews, the shelter itself is just a part of a whole four-step path developed by the architect, designed to help people get out of homelessness and back on their feet.

FIGURE 5.19 Cardborigami

§ 5.6.3 Instant Home

A similar concept, albeit not made out of cardboard, was the Instant Home designed by the author of this thesis during his studies at Wroclaw University of Fine Arts. Instant Home is a kind of portable shelter that also serves as a sleeping bag, hammock and raincoat (see Figs. 5.20-5.22). The project was realised at the Academy of Art and Design in Wroclaw, under the supervision of Prof. Wlodzimierz Dolatowski. The project was geared towards homeless people living rough. Its approach was inspired by an American group of designers called the Mad Housers, who decided to help the homeless living on the streets regardless of the fact that this is against the law. Another source of inspiration was the works of Polish designer Krzysztof Wodiczko, particularly his Homeless Vehicle Project. The idea was based on an analysis of the needs of homeless people as well as their difficulties, especially during the wintertime. Instant Home is made of the waterproof fabric Cordura®, filled with inflatable elements that serve as thermal insulation and bedding. Instant Home was tested by a group of homeless people in Wroclaw and was later displayed at the Wroclaw Contemporary Museum. The images below were drawn by a homeless artist, Zbigniew Majchrzak.

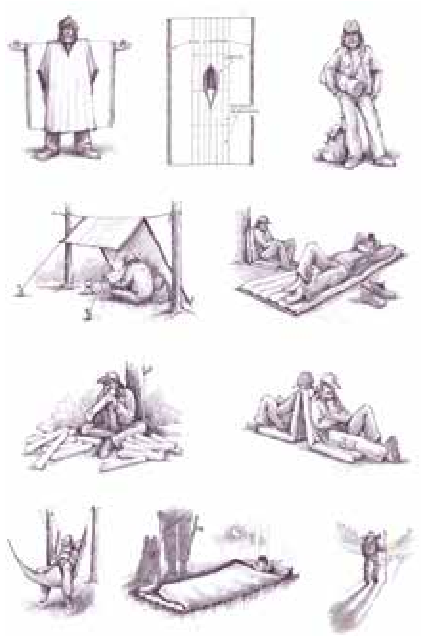

FIGURE 5.20 Sketches made by Zbigniew Majchrzak, homeless artist

FIGURE 5.21 Instant Home worn as a raincoat

§ 5.6.4 LWET – Lightweight emergency tent

Family tents are the most popular solution for shelters. Their size, shape and lifespan depend on the situations in which they are used, and on the manufacturer, climatic conditions, occupants' behaviour and duration of the period of storage before deployment. The tents most commonly used are semi-circular tunnels with a centre height of 210cm, a width of 300cm and a length of 550cm. They consist of two layers: a waterproof external layer and an inner tent. There is a 12cm continuous gap between the two layers. The floor area of the tent is 16.5m^2, which meets the minimum standards for a five-member family. Tents also come in other shapes, e.g. with straight walls, but they all have a floor area of approximately 16m^2. Tents do not provide sufficient thermal insulation, but in an emergency situation they can be used as a temporary shelter, until a proper shelter can be constructed.

After the genocide in Rwanda in 1994, two million refugees were left without homes. The first aid provided by UNHCR consisted of plastic sheets and tools with which to fell trees, so as to be able to create the structures needed for refugee tents. However, the number of structures required was so enormous that logging posed a serious threat to the woods, which might result in an ecological disaster. UNHCR responded by distributing aluminium piping for the tents. However, the precious material was sold for some much-needed cash by the refugees, and the logging continued. So instead of expensive aluminium, Shigeru Ban proposed paper tubes, which were strong enough to hold the canvas of the tents in place and moreover unprofitable (see fig. 5.23). Paper tubes were also used to build tents in post-disaster recovery attempts in Sri Lanka in 2008 and in Haiti in 2010 (see Fig.5.24). [32]

FIGURE 5.22 UNHCR tent with paper tube structure, Rwanda, 1999

FIGURE 5.23 Structure for a tent, made of paper tubes, Sri Lanka, 2008

§ 5.6.5 Paper Log House

Paper Log House is a temporary housing project first proposed by Shigeru Ban after the great Hanshin-Awaji earthquake in Kobe in 1995. A detailed description of the project is provided in Chapter 4, Section 4.3.4. The first version of the Paper Log House, which consisted of 27 pieces, was later implemented in Turkey (see Fig. 5.25), India (see Fig. 5.26) and the Philippines. Each time, the project was adapted to local atmospheric conditions and materials.

FIGURE 5.24 Paper Log House, Turkey, 2000

FIGURE 5.25 Paper Log House, India, 2001

§ 5.6.6 Training House – unbuilt

The Training House project was designed as part of the author's Master's research under the supervision of Prof. Zbigniew Bac at Wroclaw University of Science and Technology's Faculty of Architecture in 2009. [19]

The Training House was designed for homeless people living in places of collective residence. The Training House serves as a 'transitional stage' between the stages of homelessness, life in a hostel or reception centre for the homeless and life in a subsidised house. During their 6-18-month stay at the Training House, residents learn how to manage and look after their own space, under the supervision of social workers. Training houses are necessary because when homeless people stay at reception centres or hostels, they have no responsibility for the spaces they live in. This lack of training before they are granted social housing often results in homeless persons not being able to cope with their new responsibilities and thus returning to the hostel system, which is bad for both the homeless person and the Polish system of aid provided to people recovering from homelessness. The building designed as part of the project could also be used as an emergency house for disaster victims. The type of accommodation provided by the Training House is temporary housing, which can be used for up to 1.5 years before being recycled.

The purpose of the project was to create a house made of inexpensive and environmentally friendly prefabricated elements. The concept involved the creation of a framework of paper tubes with an external diameter of 200mm and an internal diameter of 150mm. The joints between the tubes were made of solid wood. The frame of the paper tubes was filled with wall and roof panels consisting of honeycomb panels and a filling of Warmcel Excel® thermal insulation material. Wall thickness was 27.5mm. The walls were covered with polyethylene film and glass fibre to protect the surface of the building's walls from damage (see Fig. 5.28).

The floor and the flat roof were made of coffers of plates of honeycomb panels stacked orthogonally or diagonally, depending on the shape of the room. The foundations were steel feet combined with a construction made of paper tubes.

The design was based on the concept of basic accommodation units with different functions (living room, bedroom, kitchen, bathroom, workshops, storage) and different shapes (triangular, rectangular, pentagonal or hexagonal in plan). By alternating and combining these shapes, the designers were able to provide 84 different spatial layouts which could be used by 3 to 42 inhabitants. There are base units, which are connected to the existing infrastructure, and supportive units, which can be changed and replaced in time (see Fig. 5.27).

One version of the project proposed a building that would act as a parasite to an existing building, benefitting from its infrastructure. Another idea was to build a complex of buildings on the land belonging to the St Albert's Aid Society in Wroclaw (see Fig. 5.26).

FIGURE 5.26 Training complex on the land of St Albert's Aid Society in Wroclaw

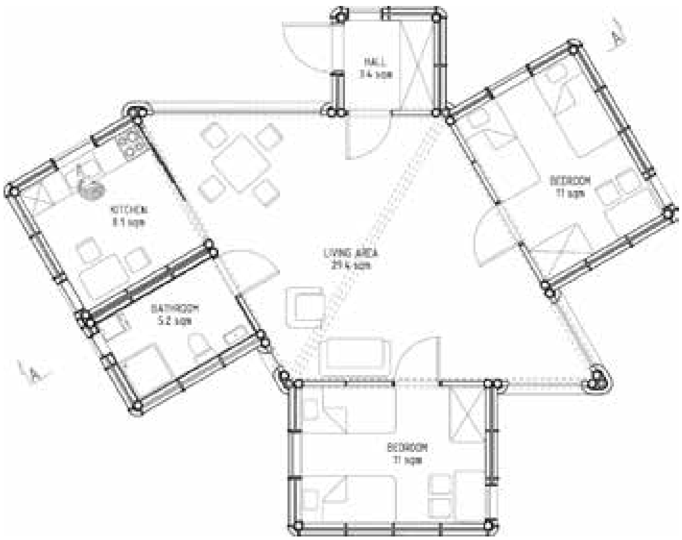

FIGURE 5.27 Training House – plan view

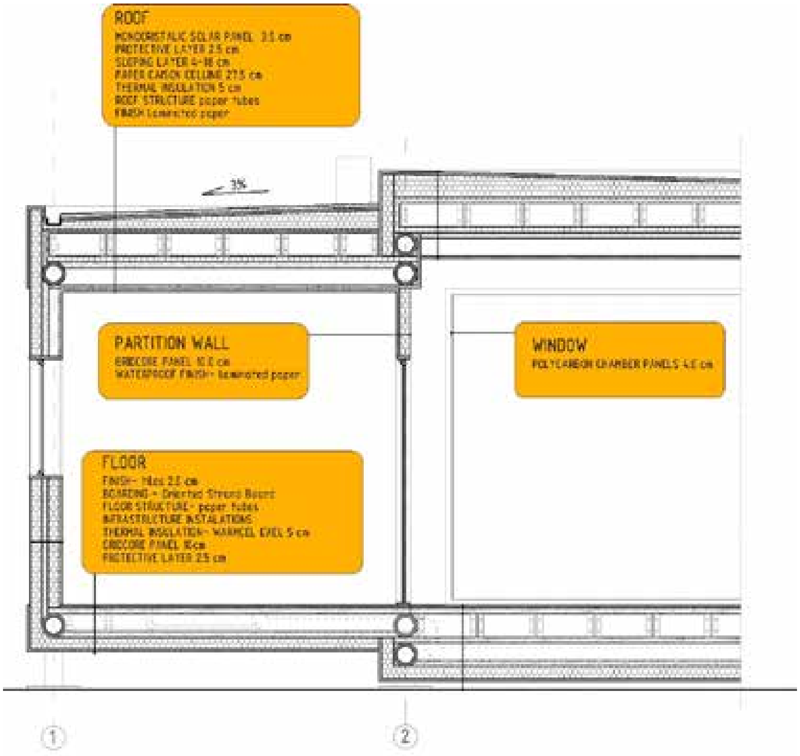

FIGURE 5.28 Training House – section

§ 5.6.7 House for victims of earthquakes in the Pacific Ring of Fire, Japanese case study – unbuilt

An interesting example of a post-disaster relief house made of paper elements is a project designed by Paulina Urbanik as part of her engineering degree from Wroclaw University of Science and Technology. The project prepared under the supervision of Dr Anna Bac was entitled 'House for victims of earthquakes in the Pacific Ring of Fire, Japanese case study'. The house is a core house type of emergency shelter designated for victims of earthquakes, designed for twelve locations around the Pacific Ocean. As the case study pertained to Japan, the project refers to Japanese culture, traditions in Japanese architecture and Buddhism. Urbanik studied people's tendency to transform temporary houses into permanent residences. She then proposed a structure made of paper, which forms the core of the house. The house is made of recycled materials.

Every house follows the same universal structure, made of paper components. This structure is made of multi-layered panels, composed of different materials, depending on the local climate and the availability of products. The houses are based on a 3x3m modular grid.

The floor area of the various types of houses depends on the number of occupants. The spaces can be enlarged if necessary – for instance, when a family's spatial needs change. The interior is an open space that can be transformed from a living room into a bedroom and back again as needed (see Fig. 5.29). [32]

FIGURE 5.29 House for victims of earthquakes in the Pacific Ring of Fire, Japanese case study

§ 5.7 Conclusions

The Arab Spring, which started in 2011, and persecution and conflicts in other parts of the globe, especially in Africa, resulted in the largest number of forcibly displaced people since World War II, reaching a whopping 65.6 million in 2016. Some 22.5 million of these forcibly displaced people were refugees, i.e., people who had to flee from their home countries due to human rights violations. Approximately 5.2 million refugees made their way to European countries. However, the largest number of refugees (13.9 million) is hosted by developing countries. In addition to refugees, the world is dealing with groups of internally displaced persons and asylum seekers. Each of these groups requires a different approach and is characterised by diverse needs. Asylum seekers are required to stay at reception centres or asylum seekers' centres while their applications are pending. Those who are granted refugee status enjoy freedom of movement and are given the right to work and/or receive an education in their host country. However, initially refugees are only given a temporary right to stay. They have to adapt to a new reality and this activation is most effective in groups, due to the costs involved and for organisational reasons. In general, refugees are accommodated in places such as planned or self-settled camps or collective centres.

It is internationally agreed that everyone has the right to live with dignity, the right to protection and the right to security. Therefore, international aid agencies and organisations such as UNHCR or the Red Cross make an effort to help people suffering difficult housing situations or living in poverty. The provided solutions consist of two parts. One is 'soft support', which consists in the provision of health care, psychological support, education and help adapting to one's new reality. The second is 'hard support', which consists of food, commodities and shelter. Architects are responsible for providing the latter. Accommodation for people affected by natural disasters or warfare has to be provided in combination with other resources. The procedures relating to, and the duration of such types of support, depend on the situation, local policy, type of threat (whether it is a military conflict or a natural disaster) and many other factors.

In many cases, refugee camps settled as an emergency and temporary solution turn into a protracted situation. Entire families are born and bred in refugee camps. The average duration of a person's stay in a camp is seventeen years. [2] However, there are many camps where refugees have stayed for more than twenty years. Therefore, refugee camps are in fact becoming refugee cities, where people still live in tents provided by UNHCR. These 'temporary shelters' are transformed, remade and extended by the camp population. It is vital that these refugees are provided with adequate shelters that satisfy their primary needs. The function-focused design approach encompasses structure and materialisation, finances and ecological issues. However, temporary housing units should be culturally appropriate for the community. At the same time, production and assembly must be simple and quick, especially when large-scale housing is needed in the short term.

It is not just about refugees, though. Homeless people in developed countries also need support and proper treatment.

Homelessness is a broad and hard-to-define problem. The ETHOS typology created by FEANTSA indicates that homelessness comes in many guises, some of which may not even be visible. Hidden homelessness is difficult to detect, which makes it hard to provide an adequate level of support. The most visible types of homelessness are rooflessness and houselessness, which are associated with people living rough, in shelters or in institutional accommodation. People living rough need support in the form of emergency shelters or temporary shelters. Those who have already decided to get out of homelessness and have embarked on an individual programne designed to help them do so will receive a house provided immediately (Housing First method) or gradually improved accommodation (Continuum-of-Care method). Homeless people must receive support at every stage of their being, but there are two crucial moments when it is particularly crucial they receive help. One of them is the moment when a person loses his/her home and becomes physically homeless. If s/he is provided with help immediately after this happens, there will be no further consequences, such as degradation and psychological identification with homeless people. Another turning point is the moment when a homeless person decides to stop being homeless. The process of leaving the insecure situation that is being homeless should be supported by appropriate accommodation that enhances personal development.

There are two main strategies for defeating homelessness in terms of housing. The Housing First concept revolves around the idea that a communal apartment supervised by social workers provides a stronger base for the fight against homelessness and exclusion, while the continuum-of-care concept is divided into three stages: prevention, intervention and integration. The accommodation provided should be appropriate to each of these stages, and the housing conditions should improve as the homeless person continues to make personal progress. Adequate housing can significantly support both strategies. It is difficult to estimate the number of homeless people due to the complexity of the problem, but the statistics show that there are almost two million homeless people in OECD countries. Worldwide there are 1.6 billion people without adequate housing. People who have fled the Middle East and Africa to go to European countries but will not be granted refugee status are in danger of becoming homeless. Thus the homelessness problem may grow significantly worse over the next few years, and it is vital that support is provided – both ‘hard support’ (housing) and ‘soft support’ (social care).

As far as the six types of refugee accommodation are concerned, planned camps in rural areas, reception transit camps and collective centres are of greatest concern to professionals who deal with designing camps. Since individual accommodation is mostly private, it is beyond the scope of management. Spontaneous camps should be avoided to the maximum possible extent.

The design of the camp should be based on the smallest social group and should take into consideration the population's gender and age structure as well as their country of origin and cultural background.

It is essential to the safety and well-being of refugees that the site of the camp be selected, the camp be planned and the shelters be built in accordance with specific criteria. Such actions should be undertaken using an integrated approach supported by specialists, with input from refugees.

The site for the camp should be chosen and prepared prior to the arrival of the refugees or people affected by a natural disaster. Several criteria should be carefully studied, such as land ownership, topography and accessibility, water supply, size of the site, the predicted maximum number of inhabitants, climatic conditions and vegetation.

The minimum size of a camp should be $45m^2$ per person. However, due to the fact that the population of the camp will grow by an estimated 3-4% annually over time, and that the refugee camp will possibly start resembling a refugee city in the end because people end up staying there for many years, an additional plot of 50-100% the size of the original camp should be reserved. The camp population should not exceed 20,000, but a population of 500-2,000 inhabitants is advisable.

The planning of the camp should have a bottom-up approach, which means that the basic structural social unit should be the family, and that a community should be no larger than one hundred people or sixteen families. The next social unit after the family is the community. Each community should possess its own services, such as a latrine (which should not serve more than twenty people), showers, water supply, rubbish collection, etc. Apart from the family and the community, camps will have the following organisational modules: a block (which consists of sixteen communities), a sector (which consists of four blocks) and a site (which consists of four sectors). The master plan should take into account not only housing areas but other functional areas and services, such as nutrition and distribution centres, health care and education, religious and cultural places, markets and places for recreation. Since there is a chance that the camp may one day turn into a refugee city, there should be enough space for daily-life activities and possibly shops in the camp.

The right shelter will provide protection against climatic conditions and serve as a transitional home, where people have their own belongings and room to live, and where they can find emotional security. The shelter should 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. A good example of such shelters made out of cardboard are the Paper Partition Systems (versions 1-4) designed by Shigeru Ban for people affected by earthquakes, who were evacuated and brought together in gyms and other public buildings that could provide large groups of people with emergency accommodation. Cardborigami by Tina Hovespian is another example of an emergency shelter, this one designed for homeless people living rough. 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 shelters tend to be tents or places in mass shelters. However, the most popular solution in emergency situations is UNHCR's lightweight emergency tents, which are used for months or even years at a time, even though the assessed lifespan of a typical UNHCR tent is 6 months. 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 such as the Paper Log House or the author's Training House. Temporary shelters and temporary housing 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 huge amount of building waste left afterwards can have a devastating effect on the local environment.

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6 Paper domes and shelters. Prototypes

Whatever you can imagine, you can also build!

Buckminster Fuller – motto of Bucky Lab course at TU Delft [1]

§ 6.1 Introduction

This part of the dissertation is dedicated to the practical approach to cardboard as a building material through prototyping. Taking a practical approach here means conducting research by design and prototyping architectural structures in which paper and its derivatives are used as the main structural material. The theoretical research and knowledge presented in the previous chapters of the dissertation will be now used as input.

The research by design and the realised prototypes will guide us to the solution that answers the question to what extent cardboard can be used as a suitable building material for emergency architecture.

The research and development of cardboard architecture used as input for this dissertation were derived from research previously conducted at TU Delft's Faculty of Architecture. The Cardboard in Architecture research group, which was set up in the department of Building Technology in 2003 and ceased to exist in 2008 due to the great fire that destroyed the building of TU Delft's Faculty of Architecture (13 May 2008), made a great contribution to this research. The fundamental and technical research was included in the previous chapters. The designs and development of products in the form of prototypes of cardboard structures are presented in this chapter.

§ 6.1.1 Previous research done at TU Delft

TU Delft's Faculty of Architecture has a long history of design and research on the application of paper and cardboard in architecture and their implementation in the form of the prototypes. In the year 1976 Chiel van der Stelt, Hans Mesem and Wim Kahman designed and built a prototype for a temporary house as part of their graduation project (see Fig. 6.1.). In 2002, Taco van Iersel, a member of the Cardboard in Architecture research group, developed a wall built from cardboard boxes as part of his graduation project (see Fig. 6.2.) In the same year Monique Verhoef designed and researched a cardboard structure as part of her graduation project. One year later, Pim Marsman and Jop van Buchem drew up a proposal for the new Stylos Bookshop which originated from a collaborative partnership between the Blob-architecture and Building with Cardboard laboratories. Joop van Buchem in his graduation project from 2004 proposed a parasite structure that was designed to be made out of cardboard.

Researchers from the Cardboard in Architecture group, in association with students of the university's Architecture and Building Technology departments, constructed a cardboard pavilion (see Fig. 6.4). The pavilion was presented at a two-day international symposium on paper and cardboard in architecture held in January 2006. Before the Cardboard in Architecture research group ceased to exist in 2008, the team realised several projects. Taco van Iersel developed his graduation project, called the Taco Wall, designed a preformed cardboard cable duct, and designed and built the Multished pavilion for a paper-recycling company in Duiven (see Fig. 6.3). Prof. Fons Verheijen designed The Wall, a sound barrier alongside the A2 motorway in which paper tubes are employed as a temporary sound barrier. The wall remained in situ for 1.5 years before being partly opened to provide some ventilation for the building behind the wall. In 2007, Prof. Verheijen and his students at TU Delft created the Transition House, a simple shelter composed of paper honeycomb panels covered by plastic canvas (see Fig 6.5). [2, 3]


FIGURE 6.1 Temporary cardboard house 1976


FIGURE 6.2 Taco Wall


FIGURE 6.3 Multished, 2002

FIGURE 6.4 Cardboard pavilion, 2006

FIGURE 6.5 Transition House 2007

More recently, research on paper in architecture was conducted by Casper Van der Meer, who defended his Master's thesis (entitled Developing the W-House) at TU Delft's Faculty of Industrial Design Engineering in 2013. Van der Meer's research included material tests he had conducted and the prototype of Wikkel House he had built with the Fiction Factory (for more information on this project, see Section 4.2.15).

Another TU Delft Master's student, Jan Portheine, built several prototypes of corrugated cardboard wall connections, which he presented in his dissertation written at the Faculty of Architecture, entitled Cardboard as a Construction Material for Beach Houses (see Figs. 6.6 - 6.8). Since 2015, Portheine and his colleague Wout Kommer have produced Kartent, cardboard festival tents that can be 100% recycled after being used. [4, 5]

FIGURE 6.6 Wall connection type A by Jan Portheine, 2015

FIGURE 6.7 Wall connection type B by Jan Portheine, 2015

FIGURE 6.8 Wall connection type C by Jan Portheine, 2015

§ 6.1.2 Research conducted by the author – general description

The author’s own practical research in the form of research by design and prototyping and material tests on paper and cardboard as a building material started in 2009 at Wroclaw University of Science and Technology’s Faculty of Architecture. In the years 2009-2012, he carried out the Paper as a Building Material research project, an examination of the potential of paper and cardboard in architecture, in association with scientific organisations affiliated with WUST and Lodz University of Technology’s Institute of Paper-Making in Poland. The project involved the Bez(do)Mnie exhibition at the Wroclaw Contemporary Museum, as well as research on water- and fireproofing and the realisation of several projects featuring furniture and pavilions (see also Chapter 5: Domains of Paper Architecture). In 2013, the author of this dissertation, then an international researcher at Shigeru Ban Studio at Kyoto University of Art and Design, contributed to the preparation for the Miao Miao Paper Nursery School project. The project was carried out by Shigeru Ban Architects and Shigeru Ban’s students and research students. The school was built during November 2013 and March 2014. The author of this dissertation took part in the first stage of construction, when the paper tube structure was erected. Together with other colleagues and members of the Voluntary Architects’ Network he worked on site in the city of Ya’an in China in November and December 2013 (see more about the project in Section 4.3.14: Miao Miao Paper Nursery School). In 2015, he built the Exhibition Pavilion of Wroclaw University of Science and Technology, which employed paper tubes as a part of a hybrid timber/cardboard structure, together with students from WUST and TU Delft (see also section 4.3.16 Wroclaw University of Science and Technology 70th Anniversary Pavilion).

In 2012, 2014 and 2015, over a dozen prototypes were designed and built by students of TU Delft, supervised by the author of this dissertation (see Fig. 1.1). The projects carried out as part of the Bucky Lab course that is part 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 author of this dissertation to examine more closely different structural, geometrical and material solutions used in paper architecture. It was the last series of cardboard prototypes supervised by Prof. Mick Eekhout before he retired from TU Delft in March 2015. In 2016 the author’s most recent project, an emergency cardboard shelter called TECH 03, was executed in the city of Wroclaw. The project was the result of previous research conducted by the author and was built in cooperation with Wroclaw University of Science and Technology and TU Delft.

§ 6.1.3 Projects and prototypes

The following section is devoted to practical research that encompasses design by research and prototyping. The projects presented here will be described and analysed in terms of geometry, structure, size, applied paper products of the packaging industry, the composition of the materials, connections between the elements and the components, possible production techniques and implementation. Furthermore, the potential for further development and application of the projects or parts thereof will be discussed as recommendations for further research.

The projects and prototypes were realised within the scope of Bucky Lab, a first-year Master's course that is part of the Architectural Engineering and Building Technology tracks taught at TU Delft's Faculty of Architecture and the Built Environment. The Bucky Lab is a block of courses supervised by Dr Marcel Bilow. It consists of Bucky Lab Design, where students design their project from the first sketches up to shop drawing; Bucky Lab Production Techniques, where the projects are built in the form of prototypes, either to scale or at a smaller scale; Computer Aided Design and Modelling; Structural Mechanics and Material Science.

§ 6.2 Cardboard shelter and dome prototypes

The following projects and prototypes represent the wide variety of domes and shelters that are made out of paper products and can be used as emergency shelters. The products incorporated into the projects were paper tubes, honeycomb panels, corrugated cardboard, paper board and L- and U-shapes made of paperboard. These products are mass produced by the global paper-making industry, which means they can be purchased at a low price almost anywhere. More information about the products and their properties can be found in Chapter 2. In addition to focusing on low-cost products, the students were instructed to design buildings that were easy to construct, store and transport and featured building elements and components that were so easy to combine that the structures should be able to be built even by non-professional construction workers. Another requirement was the possibility of organising the structures in groups or clusters so they could form bigger constellations designed to serve groups of people in need of large-scale accommodation.

The projects had to fall into the medium-sized category, which meant that their complexity level should be sufficiently low that engineering consultancy companies or contractors need not be hired to build them. Because the projects had to be medium-sized, their dimensions could not exceed 5mx5mx5m. However, the structures were allowed to cover a bigger area when clustered. The students did not have to focus on impregnation of the material, but some groups did consider this issue as part of their projects. Each project was first worked out in detail. At the same time the students consulted the author of this dissertation and dr Bilow. Then each design group or individual student prepared shop drawings, and lists of materials. During the design process, prototypes of parts of the structures often had to be executed in different scales, from 1:50 up to 1:1, in order to solve structural, technical or aesthetical problems. The prototypes were then constructed during the two building weeks (see Fig.6.9). Most of the projects were realised in 1:1 scale and presented at an exhibitions at TU Delft (see Fig. 6.10). Each project took about five months to complete. The final documents about the projects, i.e. the reports describing all the projects, were the source of the information and figures presented in the following section.

FIGURE 6.9 Workshop with Bucky Lab students at TU Delft, 2014

FIGURE 6.10 Exhibition of the prototypes produced by Bucky Lab students at TU Delft, 2014

§ 6.2.1 Cardboard Pop-Up Dome

Type of structure: folded plate structure
Realisation: January 2013
Location: TU Delft
Authors: Dwayne van Halewijn, Leon Zondervan
Design supervision: Jerzy Latka, Peter van Swieten
Prototyping supervision: Marcel Bilow, Jerzy Latka

The pop-up dome was a lightweight transportable and foldable cardboard structure. It was designed to be a shelter for different kinds of uses. The dome could be used as a shelter in refugee camps or places where natural disasters had struck, or alternatively, it could be used at festivals, fairs, etc. The dome had a folded-plate structure based on origami folding. The prototype was made from five layers of 7mm corrugated cardboard sheets, connected with glass-fibre-reinforced tape. The dome was 2.5m high and 4.5m in diameter (see Figs. 6.15 and 6.16). Once it was folded down, its dimensions were 2m by 0.5m. It weighed less than 50 kg, which meant it could be lifted by two persons. The structure was based on the 'Yoshimura pattern' from origami folding, also known as a 'diamond pattern'. The Yoshimura pattern, along with the diagonal pattern and the Miura fold, is one of the most interesting origami patterns from an architectural and structural point of view. The patterns provide three-dimensional forms with structural stability and can be modified and combined with each other. The Yoshimura pattern is named after the Japanese scientist Yoshimura, who noticed that the behaviour of a cylinder subjected to axial force follows the folds in a specific pattern, which is similar to a diamond (see Fig. 6.11). [6]

FIGURE 6.11 Yoshimura pattern on a cylinder [6]

The pattern consists of rhombuses, which are divided into triangles. The lines that are at the borders of each rhombus must be folded as mountains, and the lines that go across the rhombus must be folded as valleys.

The cardboard pop-up dome consisted of eight large triangles connected to each other sideways. Each of the triangles could be divided into fifteen rhombuses or thirty smaller triangles (see Fig. 6.12). By rotating the structure by approximately 100 degrees and by simultaneously lifting the octagonal roof panel, users were able to fold a small package into a full-size dome. All the walls (eight triangles) expanded when the structure was rotated and lifted vertically. With the help of five persons, the dome could be unfolded within two minutes (see Fig. 6.14).

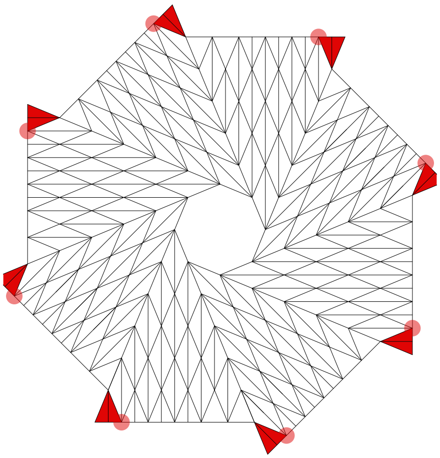


FIGURE 6.12 Fold pattern for the dome

FIGURE 6.13 Prototype of sloping hinges

The corrugated cardboard triangles were connected to each other with reinforced translucent duct tape. The basic problem was the thickness of the panel, which was hard to predict at this phase of the design. When a triangles was folded in, the thickness of this panels was cascading. Therefore, the hinges had to connect two cascading edges. The solution the students researched was a sloping hinge with solid cardboard beams and a 10mm gap between the big triangles in order to obtain a linear hinge (see Fig. 6.13).

The roof element was an octagonal plate added to the top of the dome. Piano hinges were used to connect the roof plate, to prevent the tape connections from tearing. The hinges were bolted to the cardboard, and by use of big washers forces were distributed over a bigger surface to prevent tearing of the material.

The project was developed in three stages. In the first stage, when the primary design was drawn up, a 1:3 scale model was built in order to check the stability of the structure. In the second phase, the model was rebuilt and the plate connections were worked out in greater detail. Later one-eighth of the dome was built with a scale of 1:1. The third stage was a complete 1:1 prototype.

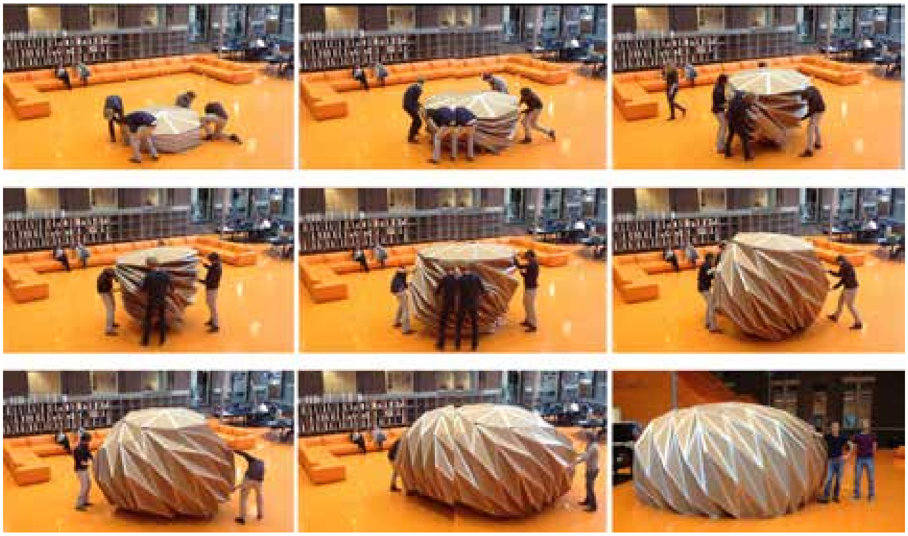


FIGURE 6.14 Opening the dome

FIGURE 6.15 1:1 scale prototype of the unfolded dome

FIGURE 6.16 Interior of the dome

Evaluation

The idea and realisation of using a folded plate structure to create a pop-up dome were successful. The most difficult part was finding a proper solution for hinges. The sloping hinges allowed the plates to be connected with each other while the thickness of the panels changed along the side of panels. The use of reinforced duct tape and piano hinges made the structure sufficiently strong and ensured that the various parts of the structure were well connected. The structure was built as a prototype in 1:1 scale and proved stable. However, the material used, five-layered corrugated cardboard, seemed to be too wiggly. If strengthened, the structure could be used as a formwork for further reinforcement with, say, a thin layer of concrete or epoxy poured onto the outer surface. The corrugated cardboard could be replaced with honeycomb panels, which would be thicker and stiffer but also lighter. Sandwich panels made of cardboard and some insulating material, like Styrofoam or polyurethane, would be a promising solution. The other option would be sandwich panels with aluminium sheeting on both sides. Yet the dome would not be used for emergency situations but rather for profitable events like festivals, exhibitions or trade fairs. The most valuable aspect of the project was the foldable mechanism that would ease storage and transportation and allow the structure to be erected quickly in an emergency situation. In general, origami and its folding techniques are a rich source of inspiration for architects, and should be investigated in the future as a solution for usable emergency structures. Although the prototype seemed to work correctly, issues such as windows, ventilation or openable doors would arise in reality. Ventilation openings were created in the octagonal roof plate, but the doorway rendered the structure more unstable. The greatest qualities of the project were its bold and unique appearance and beauty, as well as the ease with which it could be transported. The pop-up dome can be erected as a standalone or in a group. Further research should consider its connection to the ground (slab or anchors) and thermal insulation.

§ 6.2.2 6.2.2. SCOLP (Structural Connection of Laminated Paperboard)

Type of structure: shell structure (geodesic dome)
R**ealisation:** January 2013
Location: TU Delft
Authors: Patricia Knaap, Bram Teeuwen
Design supervision: Jerzy Latka, Peter van Swieten
Prototyping supervision: Marcel Bilow, Jerzy Latka

The idea behind SCOLP was to design and build a dome that consisted entirely of cardboard elements, including the connections.

Several types of geodesic domes with frequencies ranging from 1V to 6V were considered. In the end, a 2V-icosahedron-based dome was selected for prototyping. All icosahedron geodesic domes have six 5-way connections. The most basic shape, a 1-frequency (1v) icosahedron dome, consists of 20 equilateral triangles. A 1v dome has just one strut between two neighbouring 5-way connections. A 2v icosahedron dome has two struts between the 5-way connections. As a result, the basic triangular form 1v is divided into two. Higher-frequency domes have more subdivisions of the basic shape (1v) which also results in more connections and struts (see Fig. 6.17). Moreover, an even-frequency dome has a dividing line exactly across the centre of a sphere, while odd-frequency spheres have to be divided slightly above or below the centre line. This is why 3v domes do not have a flat base and come in three-eighths or five-eighths versions. In this case, a sphere was cut in half and the resulting dome was placed on the ground and all the anchor nodes were positioned in one plane. A 2V icosahedron dome has three types of connections: ten 4-way connections which are at the bottom of the dome, where they serve as anchor points; six 5-way connections, four of which are located in the middle of the dome and one at the top; and ten 6-way connections. The 5- and 6-way connections are alternated. In a 2V dome the struts only come in two different lengths, so there were thirty-five 'A'-type tubes measuring 1.70m and thirty 'B'-type tubs measuring 1.50m. The tubes had an internal diameter of 60mm and the walls were 5mm thick. The radius of the dome was 2.75m (see Fig.6.18).

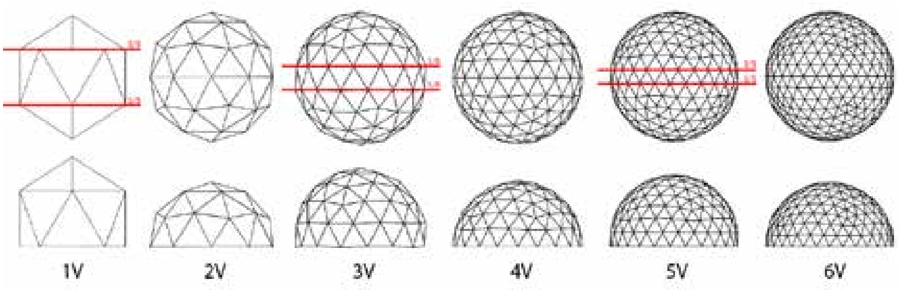


FIGURE 6.17 Geodesic sphere and dome structures with different frequencies

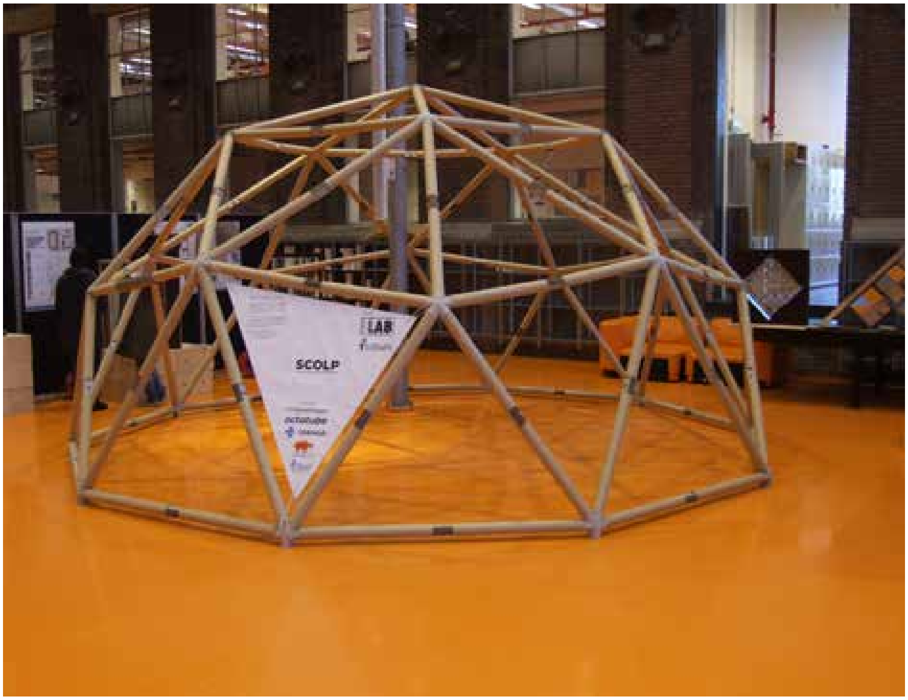
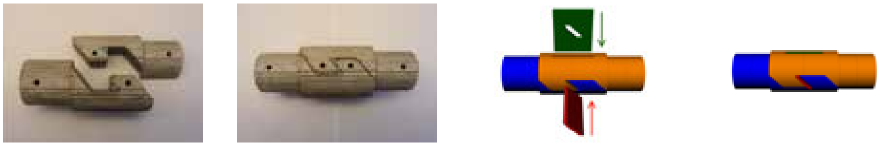


FIGURE 6.18 1:1 scale prototype of SCOLP

As the idea behind the project was to build a dome entirely out of cardboard, including the tubes and nodes, the connections between the paper tubes also had to be made of cardboard.

A dome was constructed using hollow paper tubes and massive laminated connections made of fully laminated paperboard. Connecting the dome rods in the 4-, 5- and 6-way connections was problematic, because all the parts had to be connected at the same time. Therefore, the connectors were moved to the middle of the rods. In other words, the 4-, 5- and 6-way connections were designed as solid and stiff connections in the form of a starfish, but the paper tubes were cut into halves and connected at the halfway point by means of specially designed locking cardboard connectors (see Fig. 6.19). The connectors in the middle of the rods consisted of two parts, each of which had a hook that perfectly fit into the part. The starfish-shaped connectors were connected to the paper tubes by rotation parallel to the surface of the dome (see Figs. 6.20 and 6.21). Both the starfish-shaped connectors and the hook-shaped connectors were prefabricated out of laser-cut and laminated layers of 3mm thick paperboard. The midway connectors, having been inserted into each other, were locked with cardboard wedges.



1 *2* *3* *4*

FIGURE 6.19 Laminated cmidway ardboard hook-like connector; **1** seperated; **2** connected; **3** locking with cardboard wedges; **4** locked midway connector

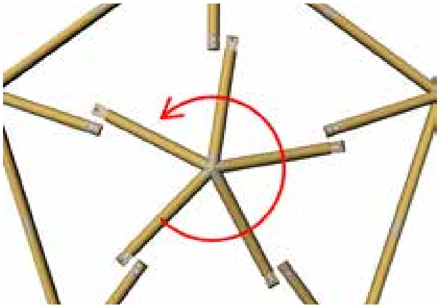


FIGURE 6.20 Starfish-shaped connection and method of assembling the dome elements

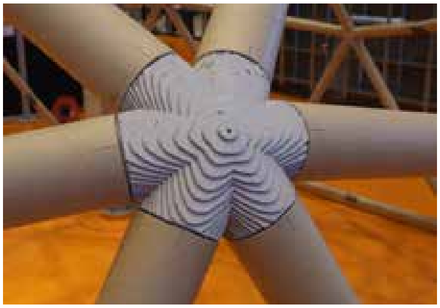


FIGURE 6.21 Starfish-shaped connection

Evaluation

The SCOLP project showed that it was possible to produce a structure entirely out of cardboard. However, the production of laser-cut, laminated and then sanded nodes proved expensive and time-consuming. If a bigger dome had to be erected, even thicker nodes would be required. The maximum thickness of the paperboard was 5mm due to the production and drying process. The idea of midway connections made it easy to erect the dome, although there was still a stability issue to be solved by means of a rigid cylindrical sliding tube. If the connections were made to coincide with the 4-, 5- and 6-way starfish-shaped nodes, both design and production would be much more complicated and the erection process would require more people in order to fit all the elements together at the same time. When covered with canvas, SCOLP could serve as a primary shelter. When scaled up, it could be used as a gathering place or social room for communities. However, the amount of work and complexity involved in the production of the nodes suggests that it might be better to use connectors made of wood or steel. The dome could be transported in the form of prefabricated star-shaped components and could be erected on site. As the midway connectors were easily combined, the construction process could be accomplished by non-professionals. However, if the nodes were made of cardboard, as in this project, said nodes (particularly the anchor nodes) would require impregnation to prevent damage caused by water.

§ 6.2.3 Curved-fold dome

Type of structure: Shell structure (geodesic dome)
Realisation: January 2013
Location: TU Delft
Authors: Dennis IJsselstijn, Pedro Calle
Design supervision: Jerzy Latka, Peter van Swieten
Prototyping supervision: Marcel Bilow, Jerzy Latka

This curved-fold dome is three-eighths of a 3V-frequency geodesic dome based on an icosahedron shape. The project was mostly focused on one element: the strut, which was produced in series that ended up making up the entire structure. The struts thus produced were folded from a single sheet of corrugated cardboard (see Figs. 6.23 and 6.24). The curved folding pattern led to a strut curved in two directions, so that it would satisfy the compression and tension strength requirements. The struts were made of five-layered corrugated cardboard recycled by the students from bicycle boxes.

FIGURE 6.22 Curved Fold Dome, 1:1 scale prototype

The dome was 7 metres in diameter. It consisted of three types of struts: 30 x Type A with a length of 1.22m, 40 x Type B with a length of 1.41m and 50 x Type C with a length of 1.44m. The total volume of the unfolded dome was 0.9 and it weighed 54 kg (see Fig.3.22).

The dome had 46 joint members in the form of pentagons and hexagons. They were made up of four laminated layers of corrugated cardboard, which overlapped with the ends of struts. The joints and struts were held together with zip ties (see Figs. 6.25 – 6.27). The zip ties worked in two ways. On the one hand, they kept the cardboard elements together. On the other hand, they provided extra shear resistance between the cardboard layers.

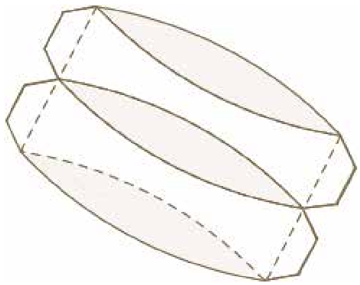


FIGURE 6.23 Folding pattern of the struts

FIGURE 6.24 Folded struts

FIGURE 6.25 Joint members between the dome's struts

FIGURE 6.26 Scaled model of the joints between the struts

FIGURE 6.27 Joint members connected with struts by zip-ties

The dome was set on footers composed of folded cardboard elements. Fifteen footers held the bottom row of hexagons with zip-ties. The footers were hollow on the inside, so it was possible to fill them with something heavy for improved stability (see Figs. 6.28 and 6.29).

Structural analysis showed that 4cm thick joints could hold the dead weight and wind loads (see Figs. 6.30 and 6.31).

FIGURE 6.28 Footers being created during the production of the prototype

FIGURE 6.29 Detail of locking mechanism of footer

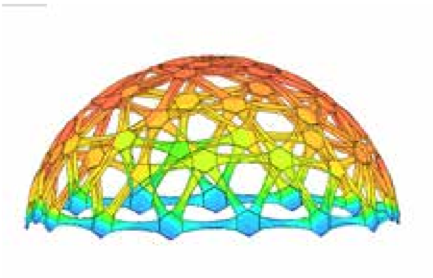


FIGURE 6.30 Structural stability analysis performed in Diana software, front view

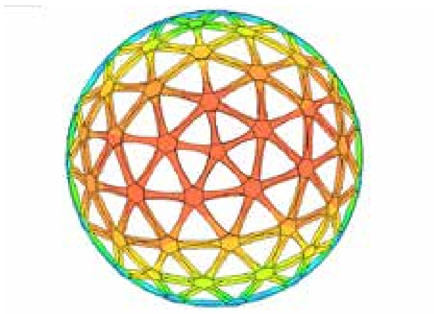


FIGURE 6.31 Structural stability analysis performed in Diana software, top view

Evaluation

This project showed how strong cardboard is if it is used in a shell structure. The curved folding method involving struts provided the material with extra strength. Five-layered corrugated board, 7mm thick, folded into struts, held the entire structure of the dome, which measured seven metres in diameter. The 5-way and 6-way connections between the struts were produced as laminated cardboard elements connected with the struts by means of zip ties. Although the material itself was strong enough, the use of zip ties damaged the cardboard because it caused point forces. The connections needed some more work. Possibly another type of material should be used in the form of a sandwich, with, say, plywood. The dome could be covered with canvas. For this reason, a connection between the structure and the canvas should be devised. The connection with the canvas could be installed in the hollow parts of the cardboard joint members. The main problem with using this structure in an emergency situation would be the doorway. Creating a door would result in reduced stability. Clearly, this is something that requires more consideration. As the struts are folded from flat plates, they can be easily stored and transported in large numbers.

§ 6.2.4 Auto-lock box dome

Type of structure: shell structure – dome
Realisation: January 2013
Location: TU Delft
Authors: Hans Haagen, Xindroe Volmer
Design supervision: Jerzy Latka, Peter van Swieten
Prototyping supervision: Marcel Bilow, Jerzy Latka

The main goal the creators of the auto-lock box dome sought to achieve was simplicity, not only in the construction of the dome, but also in its assembly and disassembly. Furthermore, they sought to make the dome foldable into small packages, and therefore easily transported. The idea behind the primary structural element was an auto-lock box. An auto-lock box is flattened when pressed in one direction and automatically assumes the shape of a box when pressed in another direction (see Fig. 6.32). In this project, the flaps of the box were designed to interlock at a particular point when the box was fully opened. Since some of the flaps were glued together, they forced the other flaps to act simultaneously (see Figs. 6.33 and 6.34). The cube-shaped element consisted of two auto-lock mechanisms on either side of the box. This solution enabled the creators to fold the box when forces were applied on the two opposite corners of the box. However, if the forces were applied to the two other corners, the box was pushed flat. To allow for the curvature of the dome, the basic elements were designed as tapered boxes. In order to achieve the curvature needed to construct a dome, the higher rows of boxes were smaller than the bottom ones.

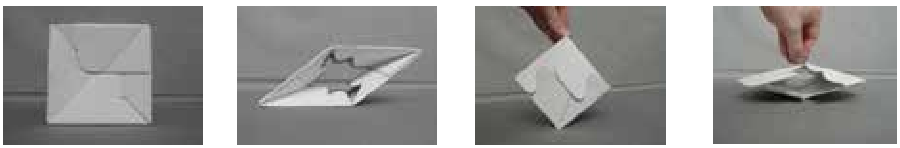


FIGURE 6.32 Folding mechanism of the auto-lock box

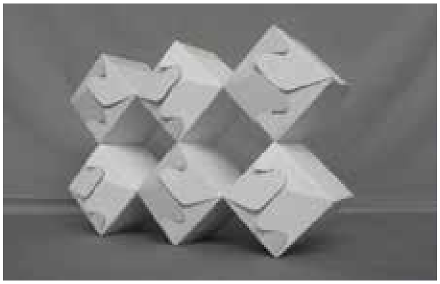


FIGURE 6.33 Folding mechanism of several auto-lock boxe, opened structure

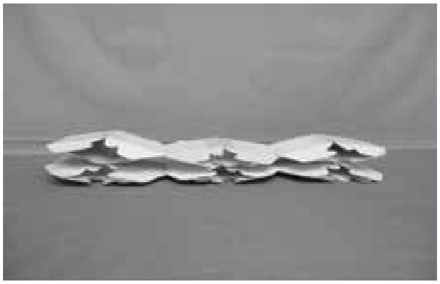


FIGURE 6.34 Folding mechanism of several auto-lock boxe, closed structure

In order to make the folded down dome easy to transport, the whole structure was divided into three main elements. The first element was the legs, which were all divided into two smaller parts. The length of each leg was approx. 4.5 metres, so they were separated into two parts with a length of two metres each. At the bottom of the dome was a tensile ring that prevented the legs from moving outwards. At the top there was a connection ring. The boxes were positioned at a 45-degree angle, so that top-down forces locked them into place and made them stronger. Because the legs were very thin at the bottom, the structure was likely to buckle. To prevent it from collapsing, a tooth-shaped tensile ring was designed to fit into the triangular gaps between the bottom boxes and connected to them by means of flaps.

Due to budget constraints, only one leg of the entire dome was prototyped. It consisted of 95 laser-cut and 26 hand-cut boxes. Thirteen different types of boxes were laser-cut from 1mm thick corrugated cardboard (see Figs. 6.35 and 6.36).

FIGURE 6.35 Visualisation of the whole auto-lock box dome

FIGURE 6.36 Prototype of one 'leg' of the dome

Evaluation

The structure of auto-lock dome shows a different approach to the use of cardboard elements in architectural structures. Although the prototype was not perfect and the boxes had to be manually opened and kept in position with special buttons added later, the idea of the smart and simple mechanism of auto-locking worked well. Such kinds of elements, flat when transported and fully formed after erection, can be used as cardboard bricks filled with polyurethane foam or some local material (such as mud) following erection. Further development should take into account the thickness and stiffness of the material and the connections between the boxes. Thicker cardboard is suggested and some parts, like the bottom (tensile) ring and its connection to the boxes, could be made from different material, i.e. wood. The idea of the folding and auto-locking structure could be applied to a simpler structure. The composition featuring boxes could be used as a prefabricated component of a wall composed of folding cardboard bricks. A component made of a series of interconnected boxes could be further developed, in a way similar to the Taco Wall (see also section 6.1.1) .

§ 6.2.5 Waffle Dome

Type of structure: Single-layered dome
R**ealisation:** January 2015
Location: TU Delft
Authors: Sofie van Brunschot, Luis Lopez, Rutger Oor, Pamela Zhindon
Design supervision: Jerzy Latka,
Prototyping supervision: Marcel Bilow, Jerzy Latka

The concept of this project was a dome built from ribs interlocking in a waffle-like structure (see Fig. 6.37). The design goal was to create a cosy personal space for people in need. The ribs were positioned in the X- and Y-direction and were made to intersect at the halfway point. Therefore, the ribs had slots cut at the halfway point. The Y-directed ribs had cuts on the upper half, the X-directed ribs on the lower half (see Fig. 6.39). The dome was symmetrical, so in total there were sixteen ribs making up a dome. There were only ten types of ribs. Another eighteen ribs were needed for the flooring. Each of the ribs was composed of three layers of double-corrugated cardboard laminated with wood glue. Each layer of the cardboard was 6.4mm thick, so the total thickness of the ribs was 19.2mm. The dome was 3m high and had a span of 3.2m (see Fig. 6.40). The area of the Waffle Dome was approximately 9m^2. It weighed approx. 70 kg. There were two entrances. The dome could be clustered in bigger groups by connecting the entrance portals to each other (see Fig. 6.38).

FIGURE 6.37 Prototype of Waffle Dome

FIGURE 6.38 Rendering of clustered domes

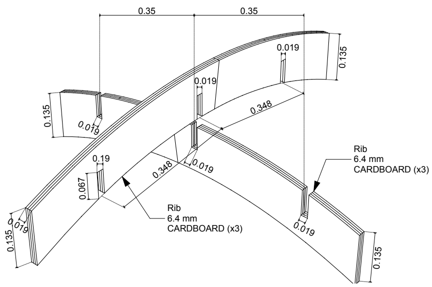


FIGURE 6.39 Prototype of Waffle Dome

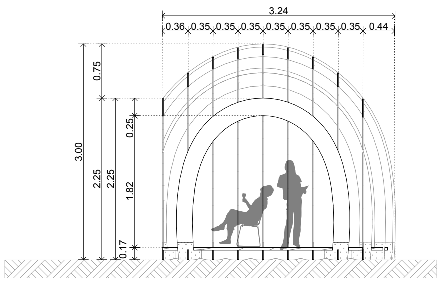


FIGURE 6.40 Rendering of clustered domes

The grid at the top of the dome could be covered by several types of materials in order to protect it from the elements and to create a layer of thermal insulation. Specially designed cardboard boxes that could be inserted into the grid and filled with thermal insulation material could make the structure more stable. However, the boxes had to be impregnated. The other option was to cover the dome with textile in such a way that it would create cushions between the ribs. These cushions or pockets could be filled with insulating material like wool, old newspapers, hay or grass. Covering the dome with translucent PVE (polyvinyl ether) fabric was a third option, and this is the one the students ended up choosing (see Fig. 6.41). Two possibilities were considered to improve the stability of the dome: cardboard L-shape profiles bolted to the corners of the dome grid, or tension cables applied diagonally between the ribs (see Fig. 6.42).

FIGURE 6.41 Composition of the structure and its cover

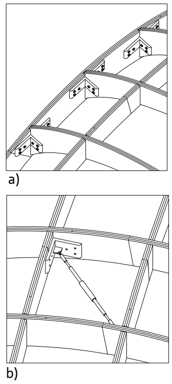


FIGURE 6.42 Concepts for stabilising the structure: a) with cardboard L-shapes; b) with tension cables

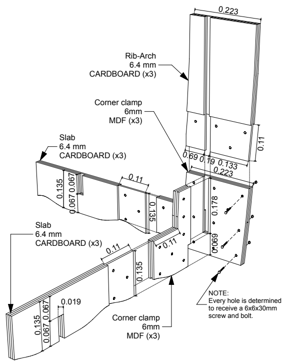


FIGURE 6.43 Connection between ribs and floor elements

The floor grid was made out of corrugated cardboard boards cut in a waved pattern at the bottom to allow water to pass through. The floor ribs were connected with the ribs that formed the dome by means of shoe-shaped wooden L-shaped joints, which were bolted to the floor and to the ribs of the dome. The ribs of the floor were covered with wooden boards (see Fig. 6.43).

The ribs of the dome could be transported as a flat package. However, since they were only 19.2mm thick, they were very wiggly, which made erection of the dome difficult. Yet once the structure was complete and all the ribs intersected, the dome had the expected level of stability. Although construction was simple and the number of elements was small, the process was harder than it should have been due to the thinness of the ribs. A few ribs actually broke during transportation and during the erection process. The estimated time of construction was 1 to 1.5 hours.

During the design and prototyping process, several mock-ups were constructed. After the students had completed the design and computation, a scale model (1:20) was built in order to check the overall look of the structure. Then a part of the structure was built in a 1:1 mock-up. This step allowed the students to check the rigidity of the rib connection and the desirable thickness of the ribs. Afterwards, a 1:5 scale model was made to check the stability of the whole structure. The last working model was a 1:1 scale mock-up of the wooden 'shoes' that connected the ribs of the dome to the ribs of the floor.

Evaluation

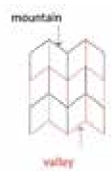
The Waffle Dome showed a phenomenon described by Shigeru Ban in the sentence: ‘Good design can create strength from weakness’. It was almost Japanese or Chinese in that it connected slender and weak timber elements in such a way that they actually gained strength. Once it had been assembled, the Waffle Dome, which consisted of elements that were merely 19.2 mm thick, displayed surprising strength. This shows that even very fragile and weak elements can result in stable structures when combined. Nonetheless, this type of structure would be too complicated to assemble in an emergency situation, when a shelter must be constructed in very limited time. The ribs proved fragile during the transportation of the parts from the production hall to the exhibition area. It is clear that they should be reinforced by some additional material or by a layer of insulation material, e.g. resin. The interlocking mechanism worked well and did not need to be strengthened by bracing or by inserting any additional material into the grid. However, in real life, if the dome were to be placed outside, the forces caused by, say, wind might prove too strong for the structure. The ribs of the floor should be made of some water-resistant material or impregnated wood. The empty spaces between the ribs could be filled to give the structure better thermal insulation from the ground. The best thing about this design was the possibility of clustering the domes in bigger groups, so they could serve small groups or communities. Another good thing about the project was the process of developing the final shape and technical elements such as connections based on several mock-ups and scale models, assisted by computational design. This helped prevent mistakes and errors in the early stages of the design.

§ 6.2.6 BYOH (Build Your Own Home)

Type of structure: Folded plate structure
Realisation: January 2015
Location: TU Delft
Authors: Chris Borg Costanzi, Andrius Serapinas, Antonia Kalatha, Dorine van der Linden
Design supervision: Jerzy Latka,
Prototyping supervision: Marcel Bilow, Jerzy Latka

The authors’ goal was to design an instantly deployable shelter that could be delivered at a certain place and be erected by unfolding a few parts within five minutes. To achieve this aim, the authors consulted examples of origami folding techniques. Their research on origami techniques focused on the Miura fold and the Yoshimura pattern, as well as their variations and corresponding folded forms. The Miura fold consists of symmetric parallelograms forming a zizag configuration in two directions. The pattern can be open at two ends. The pattern was named after the Japanese scientist Miura, who used it to create a kinetic solar system in space. [6] For an explanation of the Yoshimura pattern, see the description of project 6.2.1 (Cardboard Pop-up Dome). The main difference between the two patterns is the direction of the folds. While the Yoshimura pattern consists of a diamond folding along the diagonals, with the diagonals being folded as valleys and the edges being folded as mountains, the Miura fold forms a tessellation of the surface by parallelograms. The students combined the two patterns in order to achieve a foldable shelter in the form of a hemisphere, with an open entrance. The Yoshimura pattern was used to create the main body of the shelter, while the Miura fold was used for the creation of the entrance. This resulted in a structure that was 185cm high, 390cm wide and 420cm long (see Fig. 6.48).

FIGURE 6.44 Miura fold



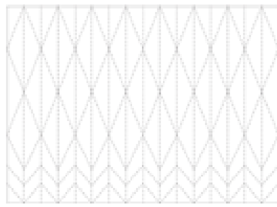


FIGURE 6.45 Combination of the Yoshimura and Miura patterns

FIGURE 6.46 1:2 scale prototype of the BYOH shelter, front

FIGURE 6.47 1:2 scale prototype of the BYOH shelter, back

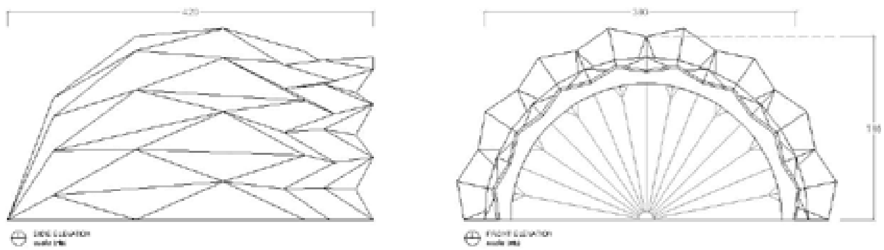


FIGURE 6.48 Dimensions of the original 1:1-scale structure

The pattern consisted of sixteen rows, each of which was composed of triangular or rhomboid panels. The panels consisted of three layers. The top and bottom were made of cardboard panels, while the cardboard in the middle had grooves that left some room for insulation material (see Fig. 6.49).

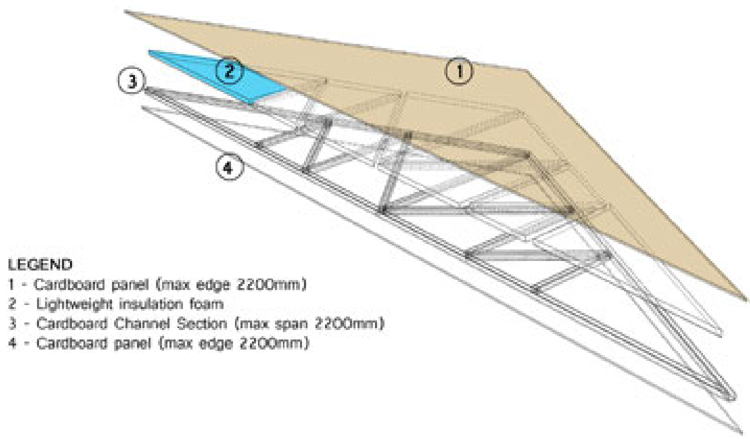


FIGURE 6.49 Composition of single plate

As origami is a folding technique involving very thin sheets of paper, the problems occurred at the very connections, where the material had to be thicker for strength and rigidity purposes. To deal with this, special hinges had to be developed to connect separate cardboard plates. A so-called ‘living hinge’ was developed for this purpose. A living hinge is a series of laser-cut lines of pre-determined length and spacing that connect the panels and allow cardboard, a non-flexible material, to bend with ease (see Figs. 6.50 and 6.51). The hinges were tested in 1:2 scale and they did their job well, but the high costs associated with laser-cutting made the hinges unusable in the final prototype. However, in a real-life situation, if the units were produced in series, living hinges would be a desirable solution as they are made from the same material as the plates. The idea of living hinges could be worked out in greater detail in future research projects involving folding cardboard structures. In this case, since the cost of the living hinge was prohibitive, another option had to be found. In the end, translucent duct tape, reinforced with fibres in both directions, was used to connect the cardboard plates, as an alternative to living hinges.

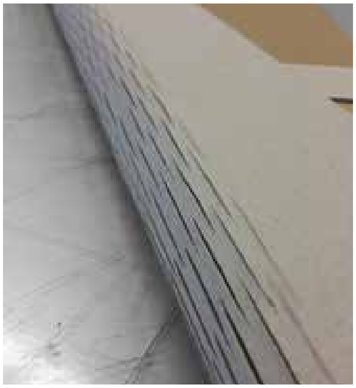


FIGURE 6.50 'Living hinge' folded

FIGURE 6.51 'Living hinge'

FIGURE 6.52 Reinforced translucent tape hinges

To create an entrance to the shelter, the origami folding pattern needed a structural element to support the doorway. An element in the form of an arch with triangles along the upper curve was incorporated. The triangles closed the structure and defined the shape of the origami structure, while at the same time providing greater stability by absorbing lateral wind forces. The arch was composed of ten layers of 6.4mm thick corrugated cardboard. The bottom parts of the arch were flanked with wooden plates that provided the laminated cardboard with stability and protection. There was a slot in the floor panel into which the entrance arch could be inserted. The arch was connected with the slot by bolts (see Fig. 6.53).

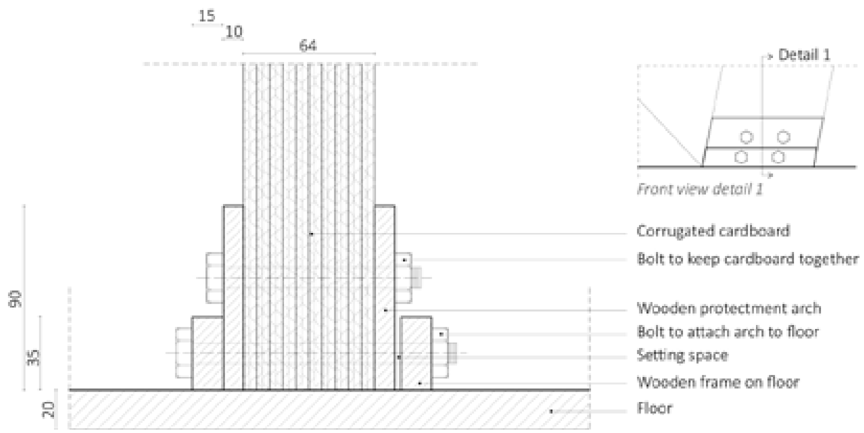


FIGURE 6.53 Composition of single plate

The connection between the origami pattern and the entrance arch along its curvature was achieved by means of elastic rope. The rope was attached to the floor after the structure was erected and opened. The floor consisted of two plywood plates and folded down under the whole structure while being transported. An additional honeycomb layer was glued to the top section of the floor panels in order to make the structure more stable. The elastic rope was also used in the back of the shelter in order to stabilise it into position.

FIGURE 6.54 Open structure with the entrance arch fitted to the floor panel

FIGURE 6.55 The structure folded down

A prototype of the BYOH was prepared in 1:2 scale. The panels were composed of two cross-laminated layers of corrugated cardboard instead of three layers with a cavity in between, as planned. The single units of BYOH could be clustered together into groups of three or even bigger complexes by means of a special corridor combined with arches (see Fig. 6.56).

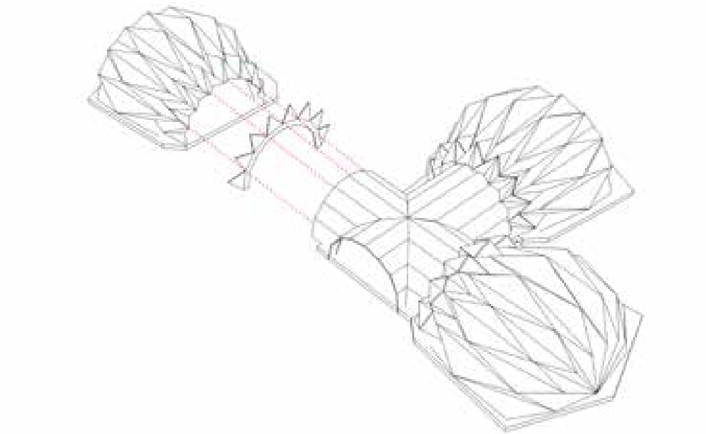


FIGURE 6.56 Possible arrangement of three shelters attached to each other by a special corridor

Evaluation

BYOH is a successful development of a shelter based on origami folding. The Miura fold and the Yoshimura pattern were combined to achieve a hemispherical space with a doorway that could be unfolded from a flat package. Further research should concern the closing of the doorway, the potential for thermal insulation and a stable connection between different elements: the floor panel, the structure itself and the doorway. BYOH is an excellent example of an instant shelter which, once set up, may be able to be reinforced in the future by pouring concrete on its outer surface. In this way the temporary shelter may be able to be upgraded to a permanent shelter, without anyone having to move out. The downside of both the living hinges and the duct-tape hinges is the thermal bridges which would occur on the whole surface of the shelter. In the original project, triangular plates were made out of three layers. The use of U-shaped cardboard elements as channels for thermal insulation material is an idea worth pursuing.

The BYOH project was awarded a prize in an international competition for emergency-housing proposals for refugees in the countries on the Mediterranean Sea, organised by the MOHA Research Center in 2016. [7]

§ 6.2.7 The Umbrella Shelter

Type of structure: Columns-and-beams rod structure
Realisation: January 2015
Location: TU Delft
Authors: Andreja Andrejevic, Li Yu Wai
Design supervision: Jerzy Latka,
Prototyping supervision: Marcel Bilow, Jerzy Latka

The Umbrella Shelter was a deployable, foldable shelter that became 3.6 times larger once unfolded. The umbrella mechanism was used twice, both at the top and at the bottom of the structure. The shelter was octagonal in plan, was 300cm high and 350cm wide and covered an area of 9m^2 when unfolded. When folded, it measured 360cm (height) by 178cm (width), with the area of 2.5m^2. When the structure was closed, the top of the roof structure slid downwards, while the bottom, which was the floor structure, moved upwards (see Fig. 6.57).

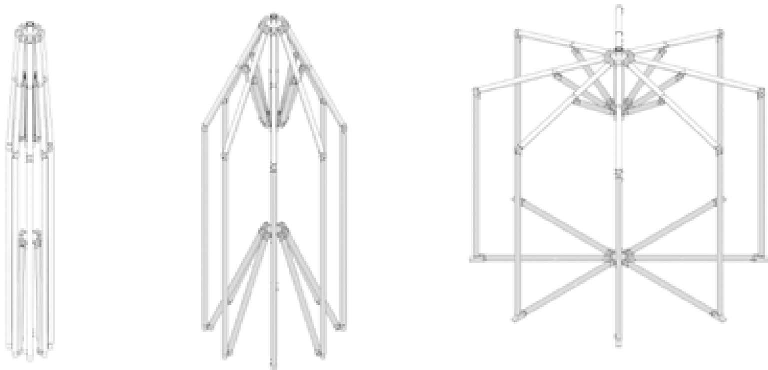


FIGURE 6.57 Folding mechanism of the Umbrella Shelter

The shelter consisted of two parts: the frame structure and the envelope (see Figs. 6.58 and 6.59). The frame structure was composed of paper tubes connected with wooden joints by means of bolts. Six different types of hinges were incorporated into the joints. The envelope came in two different versions: one for warmer climates and one for colder climates. In the envelope designed to be used in warm areas, honeycomb panels were used for the floor, while waterproof fabric was used for the walls and roof. The fabric was sewn together to form one whole, consisting of eight wall rectangles and roof triangles. The fabric was transported along with the structure. The fabric was connected to the paper tube structure by means of Velcro. In the envelope designed to be used in colder areas, the walls, roof and floor were combined into eight separate panels made out of honeycomb panels. In this case the honeycomb panels were installed after the structure had been unfolded. Some extra insulation material such as wool fibres, foam or cotton could be incorporated into the panel structure by adding it between the honeycomb cells. Both the fabric and the honeycomb panels were prefabricated in three different styles: one with a door, one with a window, and one in the form of plain wall (see Figs. 6.60 and 6.61).

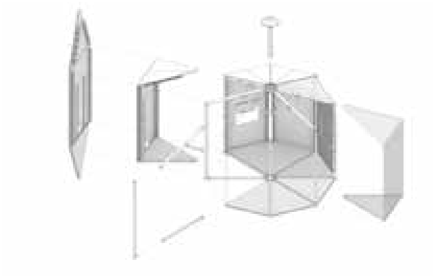


FIGURE 6.58 Exploded axonometric view of the Umbrella Shelter

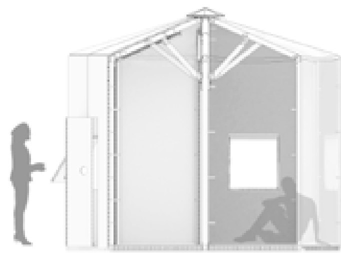


FIGURE 6.59 Section of the Umbrella Shelter

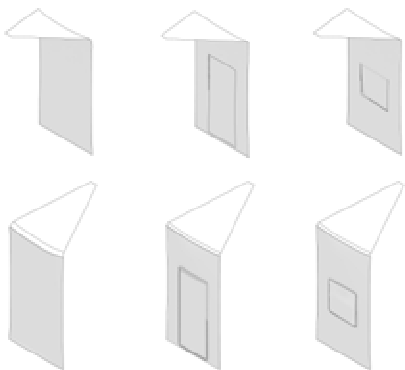


FIGURE 6.60 Type of covering made of fabric

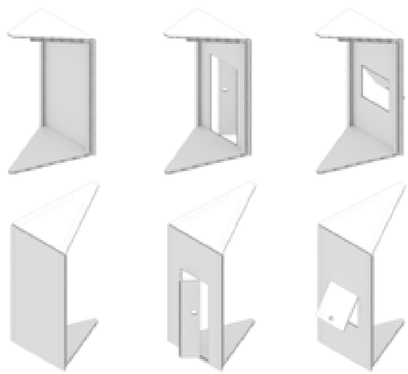


FIGURE 6.61 Type of covering made of honeycomb panels

There was a ventilation shaft at the core of the structure. The central tube, which held the structure of the roof, also served as the ventilation shaft (see Fig. 6.62 and 6.63). The central wooden ring connected with eight paper tubes held diagonally. When the shelter was unfolded, the ring was locked in position by a pin going through the central paper tube, in order to prevent it from sliding off the tube (see Fig. 6.65).

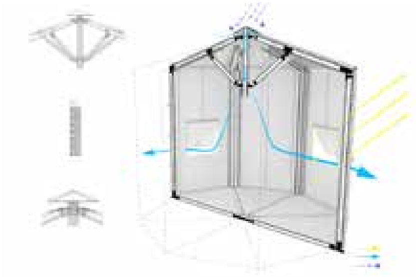


FIGURE 6.62 Ventilation method – inlet of fresh air

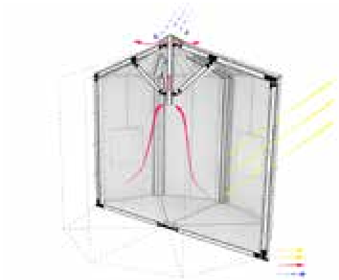


FIGURE 6.63 Ventilation method – outlet of exhaust air


FIGURE 6.64 1:1 scale prototype of the Umbrella Shelter


FIGURE 6.65 Details of the connections between the paper tubes

Evaluation

The Umbrella Shelter included a folding mechanism inspired by the mechanism of an umbrella. The greatest advantage of the project was the simplicity of the structure, which was based on paper tubes. Other pros were the fact that the process of unfolding the structure took very little time (just over one minute) and that the structure in folded form only took up very little space. The joints and connections between the paper tubes, made of laminated plywood, worked well. Prefabricated covering elements in the form of fabric or rigid insulated panels made of honeycomb allowed different arrangements of the space. The connection between the skin and the structure should be developed further in order to avoid gaps. Some of the wooden elements were too weak and broke during transportation, so the project will need improvement and further prototyping if this type of shelter is ever to be produced. The shelter with its octagonal space can be used not only as a shelter but also as an information centre, small shop or anything else that needs to be erected quickly and taken away at the end of the day. The honeycomb panels used for the walls and roof of the shelters intended for colder climates need more work, and should consist of sandwich panels, because the proposed solution (with only one layer of panels) was too thin to provide the required thermal insulation. This type of shelter is hard to cluster. They should act as single units deployed next to each other, rather than as bigger shelters for groups or families.

FIGURE 6.66 1:1 scale prototype of the Umbrella Shelter

FIGURE 6.67 Details of the connections between the paper tubes

§ 6.2.8 The HEX Shelter

Type of structure: Shield wall and beam structure
Realisation: January 2015
Location: TU Delft
Authors: Bayu Prayudhi, Priyanka Ganatra, Wan Yun Huang
Design supervision: Jerzy Latka,
Prototyping supervision: Marcel Bilow, Jerzy Latka

The main idea behind this project was to develop an easily deployable shelter that could be completely prefabricated, easily stored and transported, and unfolded in little time. The design was inspired by Japanese capsule hotels, and so called for the creation of small single-person units. However, the modular micro-dwelling would not necessarily have to serve as a sleeping unit. It could also be used as a micro-shop, storage shed, study space, etc. Thus the dimensions of the unit should fit the human scale (see Fig. 6.68).

FIGURE 6.68 Visualisation of a group arrangement of HEX Shelters

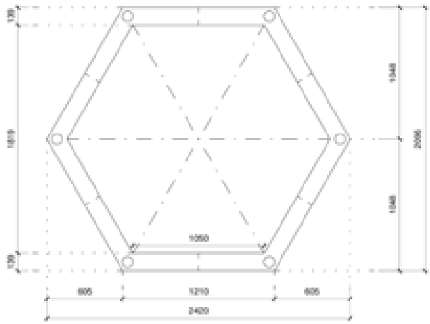


FIGURE 6.69 Dimensions of the cardboard hexagonal frame

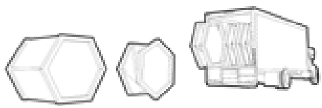


FIGURE 6.70 Folding and transportation scheme

The dimensions of the unfolded unit were 210cm (height), 190cm (length) and 242cm (diameter of the hexagon). The folded unit was approximately 70cm long (see Figs. 6.69 and 6.70). The size and folding mechanism of the shelter were governed by the transition-rotation mechanism, inspired by Jeff Beyon's origami model. [8, 9] The mechanism works like spring which extends while being rotated. The rotation angle is 120°. Therefore, the hexagons of the front and back structure stay parallel after unfolding (see Fig. 6.71). The rotation of the tube and pivot point were optimised by 3D software.

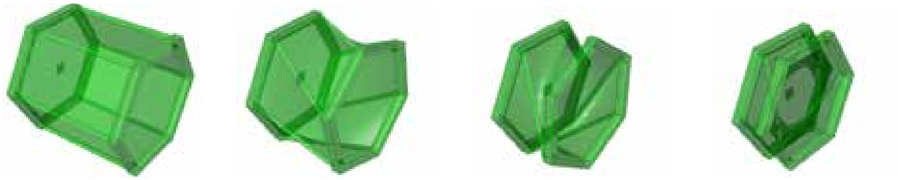


FIGURE 6.71 Spiral folding scheme borrowed from Jeff Beyon's origami model

Each unit was composed of hexagonal frames made of corrugated cardboard and paper tubes with cords inside of them that held the hexagons together. The hexagonal frame was 210cm high, 242cm wide and 15.5cm thick. The frame consisted of cross-laminated 6.4mm thick five-layered corrugated cardboard. The paper tubes were 190cm long and had an outer diameter of 85cm. Their walls were 5mm thick. The tubes were able to be connected and disconnected with a hexagonal frames. Tension cables were used inside the paper tubes. Once the tubes were connected with the hexagonal frames on both sides, the tubes were fitted into the slots in the hexagons, and the cables were tensioned and locked by means of a cable tension mechanism installed at the end of the tubes. For transportation purposes, the cables were loosened and the tubes were removed from the slots (see Figs. 6.72, 6.73 and 6.74).

FIGURE 6.72 1:1 scale prototype of the HEX Shelter

FIGURE 6.73 Detail of post-tensioned cable connection between paper tubes and corrugated cardboard frame

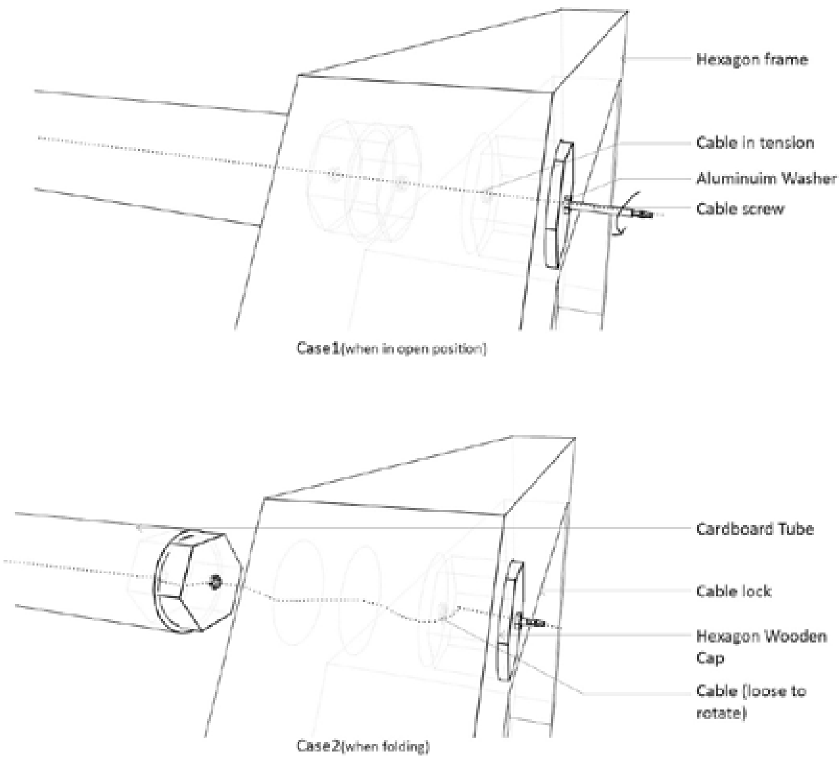


FIGURE 6.74 Detail of the connection between the paper tubes and the cardboard frame by means of post-tensioned cables

The skin of the shelter was made of PEVA (polyethylene vinyl acetate) fabric, which is biodegradable, and non-chlorinated vinyl, commonly used for shower curtains. The fabric was wrapped around the tubes and fastened with Velcro. The floor was a sandwich of honeycomb panels and OSB boards (Oriented Strand Board or flake board) on both sides of the honeycomb. During transportation the floor panel hung from the hexagonal wall panel and so was integrated with the whole structure. A door consisting of honeycomb panels provided entry to the shelter. There were two rectangular door panels in the middle and two triangular panels on the sides.

Evaluation

The idea of folding down the structure by means of a spiral movement worked fine. The folding motion required that the cords in the form of tubes from the hexagonal frames be disconnected, which somewhat complicated things. During this process the outer skin had to be detached. The skin and its connection to the structural frame should be developed further so as to reduce the risk of leakage. Another option would be to make the envelope out of some rigid detachable or foldable plates, like honeycomb panels. This would allow the shelter to be used in different climatic conditions and provide additional thermal insulation. If the envelope were made out of rigid detachable or foldable plates, they should be demountable and shipped together with the floor panel in one package. Otherwise, this shelter will be a cell that is half cardboard, half tent.

The hexagonal frame, composed of corrugated cardboard, was lightweight and strong enough to carry the floor panel loaded by 5 people and to bring stability to the whole structure. However, it was debatable if this particular use of cardboard exploited its best properties. A wooden frame would work better for this type of structure, which was proved by the Octagon Shelter, designed and built by Anna Wikiera, Katarzyna Dominiak, Aleksandra Nowotniak, Justyna Romanowska and Dorota Reclawowicz during the 2016 Summer School of Architecture (Living Unit). In this project, the same principle was used, but with an octagon instead of a hexagon (see Figs. 6.75 and 6.76). [10]

FIGURE 6.75 Octagon shelter designed and produced during the 2016 Summer School of Architecture (Living Unit)

FIGURE 6.76 Octagon shelter folded down

In actual fact, cardboard was not good enough for this project. However, it was a good way to test the behaviour of laminated corrugated cardboard under compression caused by post-stressed tubes, with positive result.

§ 6.2.9 Wing Shelter

Type of structure: Shell structure – hyperbolic paraboloid
Realisation: January 2015
Location: TU Delft
Authors: Eleftherios Siamopoulos, Ioanna Stavrou, Sander van Baalen
Design supervision: Jerzy Latka,
Prototyping supervision: Marcel Bilow, Jerzy Latka

The Wing Shelter project was a lightweight structure in the form of a hyperbolic paraboloid, composed of paper-based elements. The structure was foldable, which facilitated storage and transport. The final concept was composed of several wings, each of which consisted of four paper tubes with an attached membrane made out of woven strips of paper (see Figs. 6.77 and 6.78). Since the students did not have much knowledge of how paper behaves in such a combination, some research on weaving methods and paper properties had to be conducted. The structure itself could not be said to be a proper shelter for victims of disasters or homeless people, but it could serve as a gathering place or public space for different types of activities, i.e. semi-open school, market, religious place, etc.

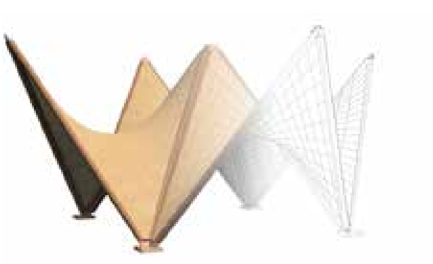


FIGURE 6.77 Perspective rendering of the whole Wing Shelter

FIGURE 6.78 Built prototype, consisting of two wings

Beams made of paper tubes were kept in position by a membrane composed of woven strips of paper. The entire unit consisted of four wings with an internal height of 3 metres at the heart of the shelter and an area of 21.16m^2. Each wing was composed of four 3.6-meter paper tubes covered with woven strips of paper. The units could be clustered together in order to cover more space (see Figs. 6.79 and 6.80).

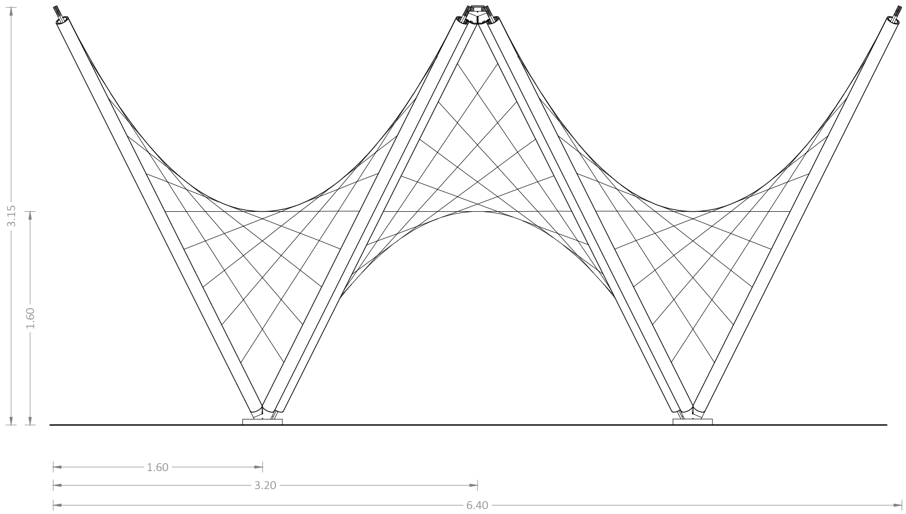


FIGURE 6.79 Side view dimensions of the Wing Shelter

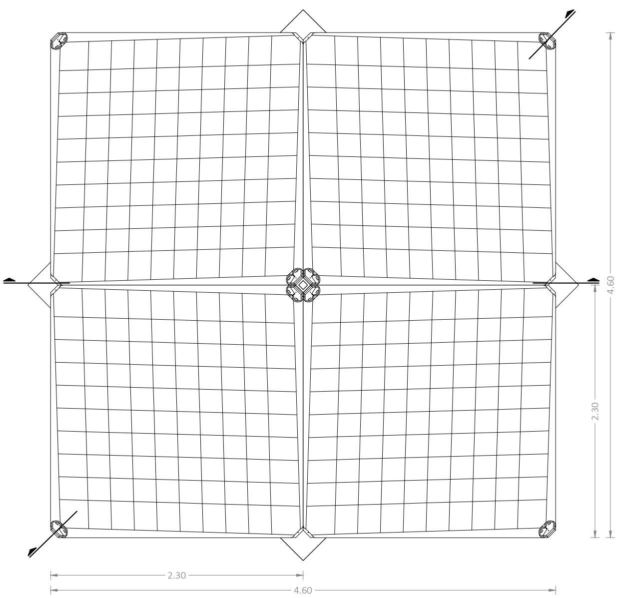


FIGURE 6.80 Plan view dimensions of the Wing Shelter

Because the paper membrane had a double curve, it was impossible to make it out of one sheet of paper. Therefore, a paper-woven membrane had to be researched. Three different weaving patterns were considered, featuring strips of paper of differing widths: a plain paper 1/1 pattern, a twill 3/3 pattern and a satin 5/1 pattern (see Figs. 6.81 – 6.83).

FIGURE 6.81 Weaving plain pattern

FIGURE 6.82 Weaving twill pattern

FIGURE 6.83 Weaving satin pattern

Next, tests on the tensile strength of the chosen paper were conducted. Two types of paper were tested: Kraft Liner Paper 60g/m^2 and Natron Kraft Paper 70g/m^2.

The first tests were conducted on a simple 20x20cm strip of paper, while the next few tests took into account the weaving pattern.

Tests were conducted involving the three aforementioned patterns and strips of differing widths. Each specimen was 20x20cm. Tensile tests were conducted using a universal testing machine (UTM) (see Fig. 6.84 – 6.86).

FIGURE 6.84 Tensile strength tests: plain paper

FIGURE 6.85 Tensile strength tests: plain pattern

FIGURE 6.86 Tensile strength tests: satin pattern

TENSILE STRENGTH [N] – PAPER TYPES					
Paper Type	Fibre orientation	Specimens			Average
		1	2	3	
Kraft Liner Paper 60g/m^2	Parallel	820.6	455.6	444.9	573.7
	Perpendicular	336.4	576.4	388.0	433.6
Natron Kraft Paper 60g/m^2	Parallel	1224	724.0	1154.6	1034.2
	Perpendicular	-	-	-	-

TABLE 6.1 Tensile strength tests results for Kraft Liner and Natron Kraft paper

TENSILE STRENGTH [N] – WAVING PATTERNS					
Waving patterns (20x20cm)	Specimens				Average
	1	2	3	4	
Plain 1x1 (2cm width)	409.1	450.9	489.2	383.4	433.2
Plain 1x1 (4cm with)	270.6	773.7	489.2	-	511.1
Twill 3x3 (2cm width)	726.395	-	596.0	663.6	662.0
Satin 3x1 (2cm width)	314.4	739.8	-	462.7	505.7

TABLE 6.2 Tensile strength tests results of different waving patterns

The structure of the Wing Shelter mainly consisted of three elements: paper tubes, paper-woven membrane and wooden connections between the paper tubes. There were two types of connections: the bottom ones, which were connected to the foundation base or were anchored to the ground, and the top ones, which held the tubes together in the air (see Figs. 6.77 and 6.78). The structure used 360cm long paper tubes with an inner diameter of 77mm and walls that were 11mm thick. The paper-woven membrane was attached to these structural elements.

In order to apply the desired tension independently to each of the strips of paper that formed a woven membrane, additional paper tubes were slid onto the main tubes in ten pieces of 36cm each. The strips of woven paper were attached to the outer paper tubes by means of dual-sided duct tape. This allowed the students to adjust the tension separately for each strip of paper. Afterwards, the outer and inner paper tubes were connected by means of nails. The membrane was woven out of ten strips of paper on each side of the structure.

'The connections between the tubes were made of laminated plywood elements. The connections were hinged, which meant it was possible to fold the entire structure in a package of 4x1 metre (see Fig. 6.87).

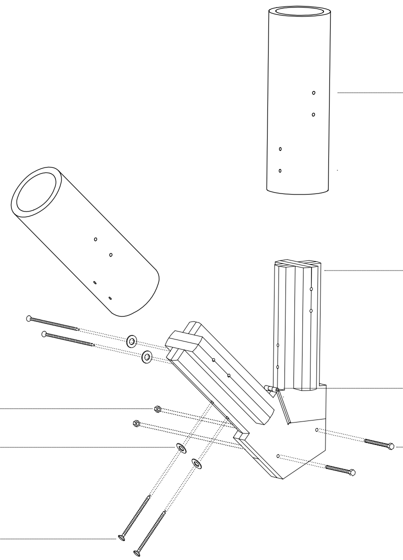


FIGURE 6.87 Detailed axonometric view of the connection in open position

Although the entire unit consists of four wings, only two were produced as a prototype due to time constraints (see Fig. 6.78).

Evaluation

The Wing Shelter project showed a new approach to using paper in architecture. For the first time, paper elements were used under tension instead of under compression. This was a better way to use the properties of paper. Paper is stronger under tension than under compression. However, creating connections with tensile elements is a big problem as paper is prone to point loads. Tensile paper elements can be connected either by clamping or gluing them to bigger surfaces. Dual-sided adhesive tape works for the second option.

FIGURE 6.88 Visualisation of a group arrangement of HEX Shelters

The hinged connectors allowed quick assembly and disassembly of the structure as well as a transformation of a big shelter into a relatively small package. Even if the project did not completely satisfy the design requirements, in that it did not create an enclosed space that clearly looked like a shelter, this approach deserves to be further worked out so as to arrive at some form of covered, semi-open spaces for public use in refugee camps (for example, for religious purposes). Triangular walls closing off the structure should be the next step of further development. Such walls could consist of honeycomb panels or corrugated cardboard plates in the form of foldable triangles attached to the paper tubes or self-standing and connected with the curve created by the woven paper. The woven strips of paper showed some inadequacy and might allow water to pass through the holes in the pattern, even if the paper were impregnated.

§ 6.2.10 The Profile: Select Your Needs

Type of structure: Columns-and-beams rod structure
Realisation: January 2015
Location: TU Delft
Authors: Eline Blom, Louisa de Ronde, Rafael Silveira, Benjamin Baron
Design supervision: Jerzy Latka,
Prototyping supervision: Marcel Bilow, Jerzy Latka

This project was all about issues associated with prefabrication, transportation, assembly, weight, adaptability and reusability.

The shelter designed by the students provided answers to all these issues. It was composed of structural components (portals), which by alternation created a different interior scheme depending on the needs of future users. Two portals were combined to form one section with a width of 1.20m (see Figs. 6.89 and 6.90).

FIGURE 6.89 Model of a single section without cladding

FIGURE 6.90 Model of a single section claded with envelope components

The sections could be attached to each other in different configurations, depending on the needs of the users. Each section was composed of four different main components: structural profiles, envelope components (roof and façade), floor components and short façade components.

Each structural portal consisted of three elements: two columns and one beam (see Fig. 6.92). The columns had different thicknesses in relation to the bending moments. The beams and the columns were composed of ten laminated layers of 6.4mm corrugated cardboard plates, reinforced with 10mm plywood at the connection points. The plywood prevented the bolts from tearing the cardboard through point loads.

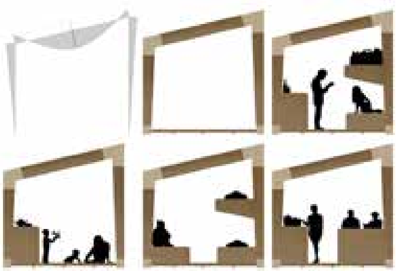


FIGURE 6.91 Different functional arrangements

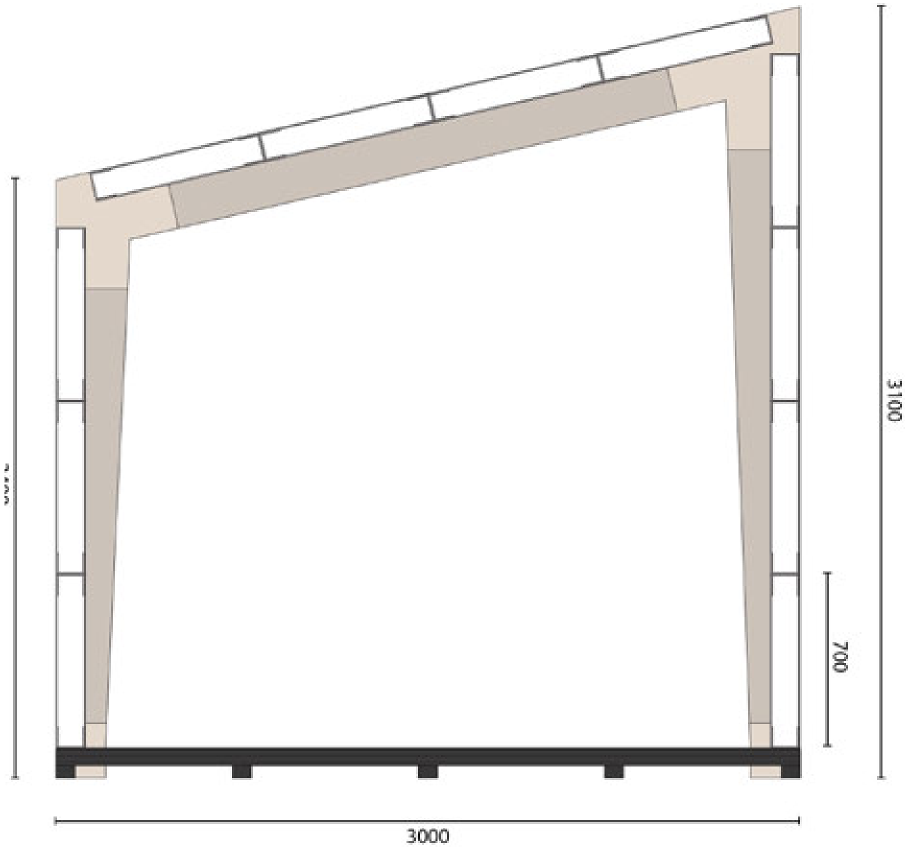


FIGURE 6.92 Structural profile

In addition to their structural role, the portals allowed the shelter to be adaptable. Different pieces of furniture were incorporated into the vertical elements (columns). These elements provided the structure with increased stability, especially in relation to lateral forces. The structural profiles were connected by the façade and roof components and allowed the shelter to be organised length-wise. Due to the fact that the different profiles could be used in different ways, it was possible to combine different functional areas, such as the sleeping zone, kitchen or living area. The shelters could also be used for other purposes: storage, study, workshop, shop, a small patient room or a meeting place (see Fig. 6.91).

The envelope components (i.e., the façade and roof components) were composed of U-profile frames held together by triangular connectors made of wood (see Figs. 6.93

and 6.94). The envelope components were produced in standard sizes and differed in terms of composition. There were typical envelope components covered from the outside with a waterproof layer of Tetra Pak material. The Tetra Pak packaging system was invented by Sweden's largest food packaging company. Tetra Pak beverage boxes are composed of six layers. From the inside to the outside, there are two layers of polyethylene, one layer of aluminium, one layer of polyethylene, one layer of paperboard and an outer layer of polyethylene (see Fig. 6.95). [11] The envelope components could be black, or alternatively they could be given a metallic finish that would reflect the sunlight and reduce the heat inside the shelter, which would be useful in warmer climates. If the structure were to be used in a colder climate, the envelope components could be filled with thermal insulation material in between the U-profiles, with a thickness of up to 10 centimetres. There were special profiles with double-glazed acrylic windows.


FIGURE 6.93 Façade component frame


FIGURE 6.94 Connections of the façade component frame


FIGURE 6.95 Cladding with Tetra Pak material

The corner elements that connected the façade elements with the roof elements were composed of honeycomb panels covered with a water-resistant finish, and L-profiles placed on their edges.

The floor components consisted of cardboard covered on both sides with 9mm OSB (Oriented Strand Board or flake board). This sandwich solution allowed the floor to distribute loads evenly on the surface. There were two different types of floor panels, one for warmer climates, and another for colder climates. The warm-climate solution was a panel composed of OSB and three layers of 2cm honeycomb panels. The version with the higher insulation value was composed of OSB panels and cardboard U-profiles with a dimension of 120x80x5mm. This created an underfloor grid which was filled up with insulation material or local soil in order to enhance thermal performance. Both types of floor panels were supported by five beams at the bottom (see Figs. 6.96, 6.97).

FIGURE 6.96 Floor sandwich composed of OSB and honeycomb panel

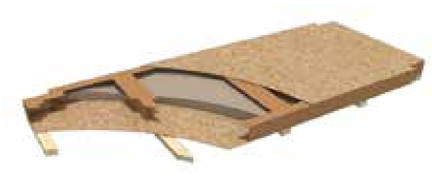


FIGURE 6.97 Floor sandwich composed of OSB and U-profile composite with cavity for thermal insulation

The short façade was the final element fixed into the structure. The short façade component was divided into three unique elements. Each of these three elements was divided into three parts which were composed and connected together in the same manner as the longitudinal façade elements. U-profiles were used as a frame, covered with a honeycomb panel and a Tetra Pak layer on top of it.

All the components were prefabricated as lightweight hybrid cardboard and wooden elements. Certain profiles could be chosen and sent to the site, where by means of basic connections with bolds they would be combined into whole shelters.

The structure was assembled section by section. Each of the sections was composed of two structural profiles, eleven façade panels, two corner elements and one floor element. Once they had arrived, the sections could be built on a levelled surface. First the floor element was laid on the ground. Then three section elements (two walls and a roof, each composed of beams or columns and envelope components) were put together in a horizontal position on the site. Afterwards, they were placed in a vertical position and fitted to the floor element. Once this sequence had been completed, another floor element could be put on the ground and the assembly sequence could start from scratch again, until the shelter had the configuration desired by the end user (see Fig. 6.98).

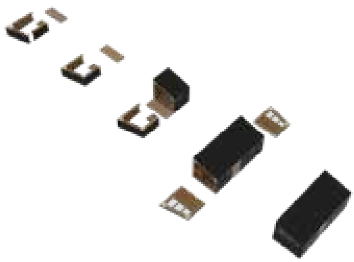


FIGURE 6.98 Assembly sequence

FIGURE 6.99 1:10 model of five sections

The sections could be clustered and connected in different ways. The structure could be lengthened by connecting the sections with the short façade. Several sections which composed one unit could be clustered in groups. Both ways of clustering, by mirroring the sections or by arranging them in a spiral shape, reinforced the structural stability of the units.

FIGURE 6.100 One section realised as 1:1 prototype with authors

FIGURE 6.101 One section realised as 1:1 prototype

FIGURE 6.102 Detail of the connection between two profiles: Tetra Pak envelope covering

FIGURE 6.103 Details of connections between wall and floor elements

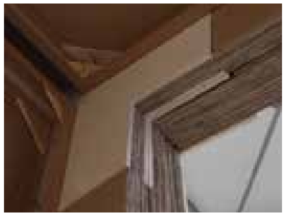


FIGURE 6.104 Details of connections between roof and wall elements

Evaluation

The *Select Your Needs* profile is a solution that can be used for both emergency houses for victims of natural and man-made disasters and shelters for the homeless in the cities. The structural composition of repetitive elements that allow one to organise one's interior space is simple and clear and allows users to engage in different types of activities. The project can be adapted to different climatic conditions. Different components with different levels of thermal insulation can be fitted to the same structural system, which means that mass production for different purposes is rendered easier. Clustering the units allows one to customise one's interior, but also allows for different layouts on an urban scale. The simplicity of the construction allows unskilled labourers to erect the profile without using special tools. The risky part is using corrugated cardboard as a structural element 300cm long. When the structure was produced, pillars consisting of corrugated cardboard deflected during the process of lamination and drying. The pillars had to be clamped to the flat surface in order to avoid deflection during the lamination process. The main idea could be further developed by the use of different materials for the structural parts. Instead of corrugated cardboard, paper tubes or L-profiles could be employed. Further research should be carried out on creep of the material and the influence of the climate and the weather. Lightweight, prefabricated elements that can be combined into different arrangements should be further researched. Another part worth of further development was the envelope layer made of Tetra Pak carton board.

§ 6.2.11 Box shelter

Type of structure: Plate wall structure
Realisation: January 2015
Location: TU Delft
Authors: Juliette Goldbach, Wilem Koenen, Teun Kruip
Design supervision: Jerzy Latka,
Prototyping supervision: Marcel Bilow, Jerzy Latka

The Box Shelter was a shelter for victims of natural and man-made disasters or for refugees who have fled war zones. The shelter could be shipped to the site in a package, where all its elements would be assembled. The structure was lightweight and easily transported in the form of a package whose dimensions were 2.4 by 4.7 metres. Four of those packages fitted into a 20-foot shipping container.

The shelter could be unfolded by its future users or by unskilled labourers in several steps. In other words, the erection process and mechanism were user-friendly and easy to operate by non-professionals, just like Ikea furniture (see Fig. 6.105).

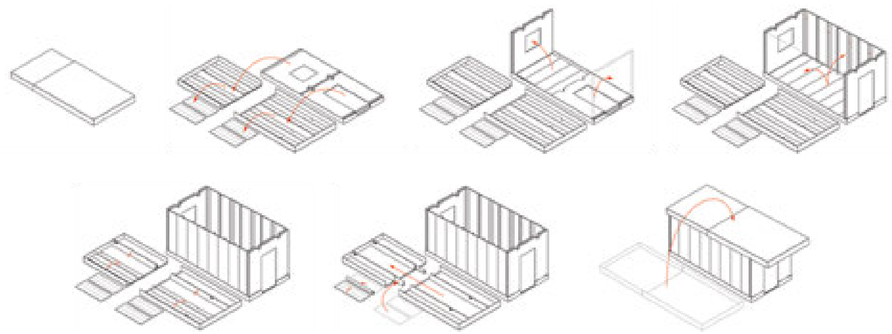


FIGURE 6.105 Construction sequence of the Box Shelter

The Box shelter could be combined with other units to form a row of shelters. Two rows in front of each other created a covered common space under the units' lean-tos (see Fig. 6.106).

FIGURE 6.106 Box shelter - visualisation

The lid of the package consisted of two parts which together made up the roof. When the lid was taken off, the remaining structure consisted of a floor and walls. The front and back walls were folded out (see Fig. 6.105). They were composed of double cross-laminated corrugated panels with U-profiles in between (see Fig. 6.110). The cavity inside the wall could be filled with thermal insulation material (lightweight foam) prior to the erection of the structure, or with local, heavier material after the unfolding of the walls. These walls were the load-bearing parts of the structure. They were connected with the floor panel through hinges placed beneath the U-shaped columns (see Figs.

6.107 – 6.109).

FIGURE 6.107 Box shelter strutre folded down

FIGURE 6.108 Box shelter structure with front wall opened

FIGURE 6.109 Box shelter structure with front and side walls opened

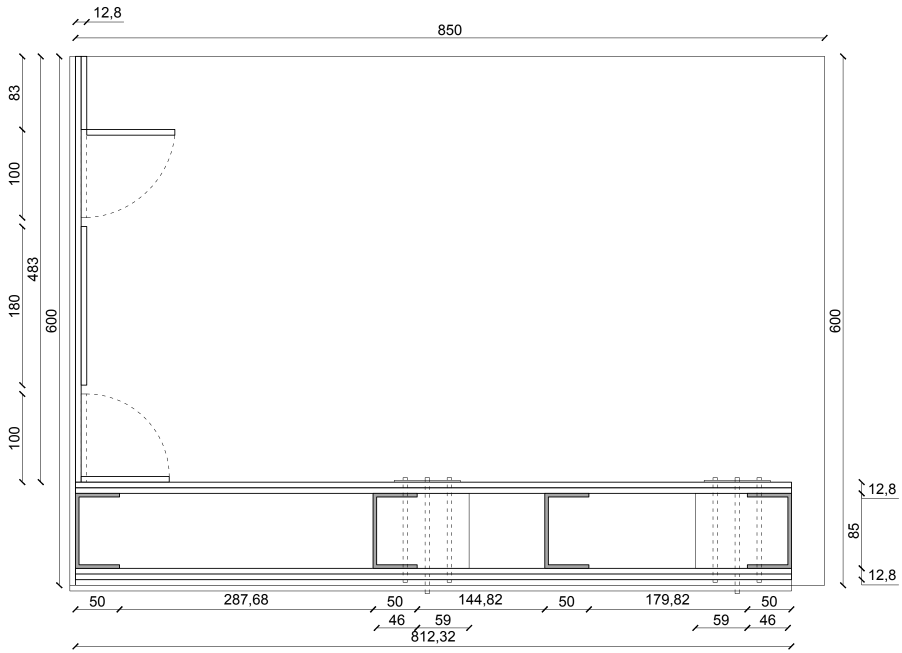


FIGURE 6.110 Detail of the load-bearing wall structure

FIGURE 6.111 Axonometric view of the structural elements of the Box Shelter

After being unfolded, the front and back walls were held in place with tension rods and nuts. The height of the two walls differed so as to create the needed slope of the roof. The front wall was 2.40m high, while the rear one was 2.20m. The door and window were placed in these structural walls.

The side walls were thinner and composed of two layers of corrugated cardboard. In the folded-down configuration, these walls were folded under the front and back ones (see Fig. 6.110). Once the Box Shelter had been erected, the side walls did not bear any of the forces. In order to make the side walls more rigid, extra flap ribs were attached. These ribs were composed of corrugated cardboard, and after the positioning of the front, back and side walls, they were opened and clamped to the floor panel. The flap ribs also functioned as the connectors between the side walls and the front and back walls.

After the unfolding of the walls, two beams made of corrugated cardboard were folded into triangles (see Fig. 6.112). These beams served as tension rods and were connected to the roof components. The two parts of the roof – the front section (bigger) and the rear section (smaller) – were connected with two inner triangular parts of the beams. This is how the roof parts were fixed together. There were two notches in the roof beams that fitted into the notches in the front and back walls (see Fig. 6.113). Once the roof was put together, it was ready to be placed over the walls. The roof beams attached to the load-bearing walls were folded from 6.4mm five-layered corrugated cardboard.

The floor component was made up of honeycomb panels covered with plywood on either side in order to prevent damage by point loading.

FIGURE 6.112 Inner beam of the roof structure

FIGURE 6.113 Connection between the roof beam and the load-bearing wall

Bending tests were conducted in order to check if the triangular roof beams would hold the roof structure. Using a Zwick Z100 testing machine, the students tested the maximal moment by means of a four-point bending (see Fig. 6.114. During the bending tests, two metal clips were attached to the top of the beam in order to divide pressure evenly across the cardboard. Three specimens with the flat side at the bottom and three specimens with the flat side at the top were tested.

The specimens were subjected to bending with a speed of 2cm per minute and with two load points caused by one pressure head. The specimens were 1000mm long and the load points were 280mm apart from each other and 360mm from the edge of the beams. At a deflection of 100mm the machine would stop automatically due to the damage caused to the material.

The beams with the flat side at the bottom only wrinkled at the top and did not tear at the bottom (see Fig. 6.115). This was because the tensile area at the bottom was bigger than the compression area at the top. The beams with the flat side at the top tore apart at the bottom around a deflection of 40mm (see Fig. 6.116).

FIGURE 6.114 Bending tests on the Zwick Z100 machine

FIGURE 6.115 Behaviour of the beam with the flat part at the bottom – visible wrinkles

FIGURE 6.116 Behaviour of the beam with the flat part at the top – a tear in the material

The beams with the flat side at the bottom had a centre of gravity closer to the tensile area than the beams with the flat side at the top (which ended up being used in the project). Therefore, the maximal moment in relation to the centre of gravity was smaller in the beams with the flat side at the bottom.

The graph of the tests showed that there was initially a small decrease of the forces after a deflection of approximately 15mm. This phenomenon, which meant that the cardboard was settled after the first load, kept recurring during the process. It was also noticeable that when the loads were first applied, the stress-strain relation was almost linear. The stiffness values of the cardboard beam could be obtained from this linear part of the graph. The maximal moment of the beam equalled 184.2 kNmm for the beams with the flat side at the bottom and 168.4 kNmm for the beams with the flat side at the top (see Fig. 6.117).

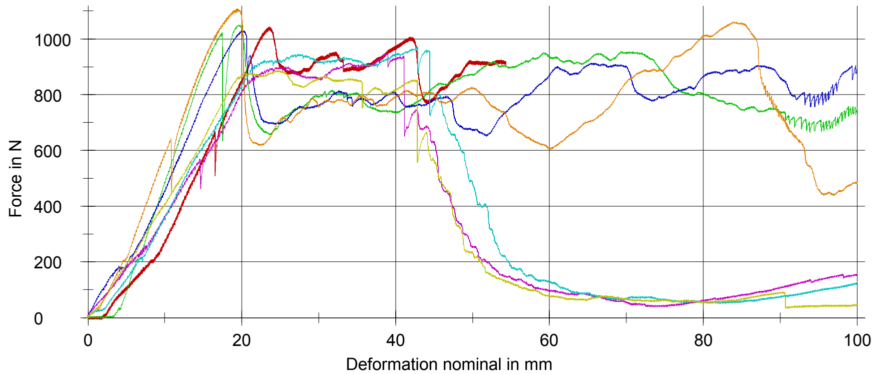


FIGURE 6.117 The graph of the bending moment tests

A prototype of the entire structure was prepared with a scale of 1:4. A prototype of the wall-and-floor connection was made in 1:1, as was the roof beam folded from corrugated cardboard.

Evaluation

The Box Shelter was a plate-wall structure. The load-bearing walls consisted of U-shaped columns covered with two corrugated boards cross-laminated to each other, so they were a lightweight and strong component – sufficiently lightweight and strong for transportation. The most promising solution the students came up with was the wall cavity, which could be filled with insulating material provided on the site. The floor panel was connected to the walls with hinges, so the whole shelter could be erected quickly. The roof was the weak part of the project. Since the roof beams were tested and found to be strong enough to carry the roof, if a problem occurred, it would probably be related to the placement of the roof on the load-bearing walls. Because no 1:1 scale prototype was prepared, it is hard to judge how difficult it would have been to install the roof on the walls. The strongest aspect of the project was its frame structure (see Fig. 6.111), clad with another material. This building components resulted in a structure that was lightweight and easy to erect. Although the front and rear walls were strong and could be properly insulated, the side walls (consisting only of a thin layer of corrugated cardboard) would not be sufficient in colder climates. However, if thicker side walls were used, the folding mechanism would no longer work properly. The hinges might also prove problematic. As they were installed in several places, point loads would occur during the erection process, with all the associated risks of material damage. Perhaps a different solution, like sliding the walls into the floor panel from above or reinforcement of the connection between the cardboard and hinges, could solve these problems.

§ 6.2.12 Papyrus Hospital System

Type of structure: Columns-and-beams rod structure
Realisation: January 2015
Location: TU Delft
Authors: Sarah Heemskerk, James Moya Jessop, Jan Kazimierz Godzimirski
Design supervision: Jerzy Latka,
Prototyping supervision: Marcel Bilow, Jerzy Latka

The Papyrus Hospital project involved a hospital system designed for people affected by the Ebola virus in Africa. The hospital, which was made of cardboard elements, could be burnt after being used in order to prevent the spread of the epidemic. The hospital was intended to be used in villages in central Africa and in rural and urban areas in western Africa. These regions are characterised by a warm and rather dry climate (monthly mean temperature is above 18°C). The rules for the treatment of Ebola state that there should be separate rooms for patients in different stages of the disease.

The main element of the hospital was the core, which contained treatment rooms that were expandable structures (see Figs. 6.118 and Fig. 6.119). These parts were expanded after the initial erection of the hospital. The core was composed of rigid and stable elements. The expandable part was composed of frames connected to each other with fabric. The core was used as a corridor between different rooms in the hospital and for storage of medical supplies. The expandable parts were designed to serve as rooms with beds in them, which could also be expanded from a small package.

The beds inserted between the frames stabilised them at the bottom (see Fig. 120).

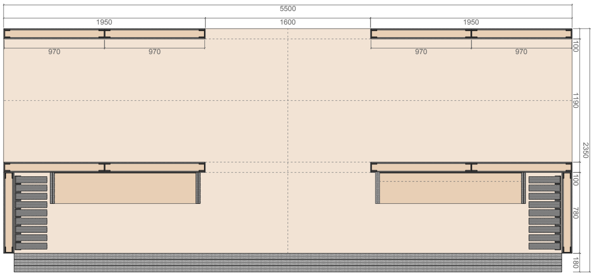


FIGURE 6.118 Plan view of the core element with folded frames

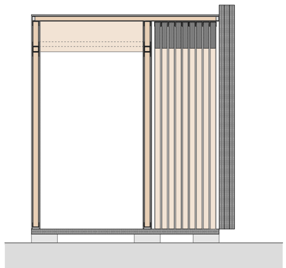


FIGURE 6.119 Section of the core element with folded frames

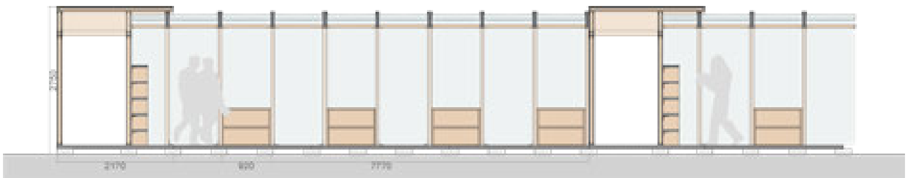


FIGURE 6.120 Section of the core element with unfolded frames

The size of the core was 550x235cm, while its height was 272cm at the highest point. In other words, the core element could be transported to the place where it was needed in a 20-foot shipping container (see Fig. 121).

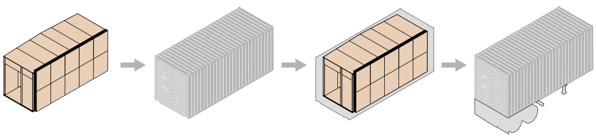


FIGURE 6.121 Transportation scheme of the folded core

FIGURE 6.122 Visualisation of the interior of the Papyrus Hospital System

The core was composed of frames clad with plates. The frames were made out of cardboard U-profiles. The U-profiles were held together by wooden blocks that were inserted between the flanges of the profiles (see Figs. 6.123, 6.125 and 6.126). The top parts of the frames were used to ensure the roof had the right height and slope. The whole structure of the core was clad with corrugated cardboard panels that overlap the frames. This improved the connection between adjacent structural elements. Each core included folded-but-expandable parts of the treatment rooms, i.e. folded beds and shelves.

FIGURE 6.123 1:2 scale prototype; core and expandable parts structure

FIGURE 6.124 1:2 scale prototype; interior

FIGURE 6.125 frame structure made of cardboard U-profiles elements

FIGURE 6.126 frame structures made of cardboard U-profiles

The expandable parts consisted of transverse frames made out of cardboard U-profiles with fabric in between. Cross beams and foldable beds with a width of 90cm were attached to the frames in order to improve the stability of the structure when the parts were expanded (see Figs. 6.123 and 6.124). The expandable part allowed the hospital system increase its area from 12.9m^2 to 52m^2, which means that its area quadrupled.

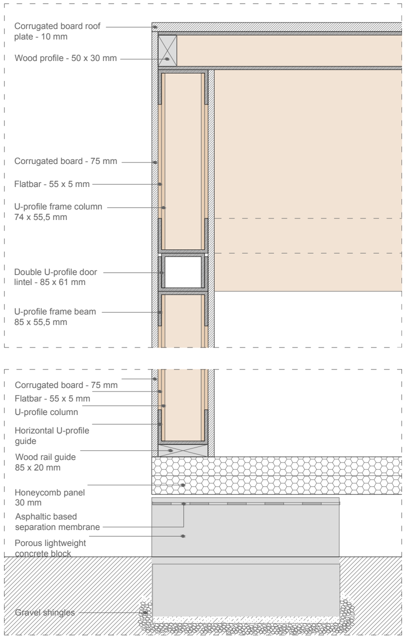


FIGURE 6.127 Detail of the longitudinal section of the external wall of the core of the Papyrus Hospital system

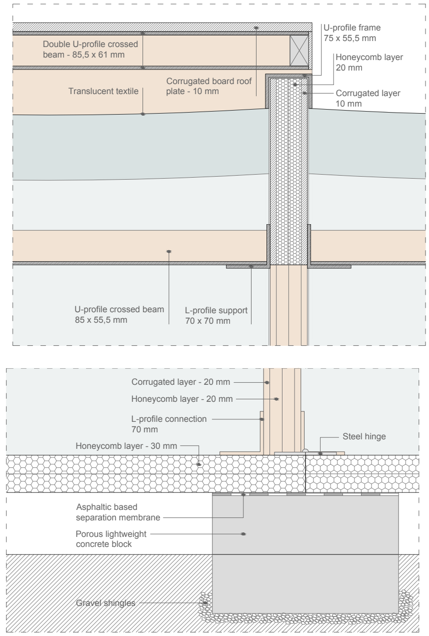


FIGURE 6.128 Detail of the longitudinal section of the expandable part of the Papyrus Hospital system

The proposed foundation was made of a porous block material. However, various solutions could be used, as long as the cardboard frame structure was raised above the ground (see Figs. 127 and 128). The prototype of the Papyrus Hospital System was built with a scale of 1:2. Although smaller structural elements were used, the structural composition remained the same.

Evaluation

The Papyrus Hospital System, which is a columns-and-beams rod structure, has good potential for further development as it provides a sustainable and suitable solution for a single-use hospital system. The elements combined into the frames are characterised by great stability and rigidness. The system of expandable frames needed to be developed with regard to stability, but the composition provided new insights into cardboard structures. Paper tubes filled with a local material or concrete could be used for the foundation. The proposed floor elements, which composed of honeycomb panels, seem to be too fragile for the area's climatic and natural conditions, so they should be replaced with wooden plates or otherwise reinforced. The general idea behind the system could be adapted to different types of emergency buildings. A U-shape frame covered with different material and filled with thermal insulation material could serve as a housing unit for victims of natural and man-made disasters. However, the expandable part would not be sufficiently insulated if this were the case. It could be used as a space for daily activities in the form of an expandable veranda attached to the house, while the insulated core could be used as a bedroom.

§ 6.2.13 Unbuilt projects

The projects described in the preceding sections were all realised as complete or partial prototypes with a scale of 1:1, 1:2 or 1:4. However, the students came up with other detailed designs for domes and shelters made of paper or cardboard. No full prototypes were made of these designs due to the costs involved, the lack of potential for further development, the lack of suitability of the shelter or the amount of work needed to complete the prototype. These unbuilt projects are presented in brief below.

Samuel de Vries worked on a cardboard tensegrity dome. A tensegrity (the word is derived from 'tensional' and 'integrity') is a structure whose compression elements are held up by a web of tension elements or cables. The tensegrity dome originated from the vertices of an icosahedral geodesic dome whose frequency is multiplied by three. The chosen frequency was v6, and a Z-like tensegrity pattern was adjusted to the dome. The dome was designed to be 2.8 metres high and have a 3.5m diameter (see Fig. 6.129). Paper tubes were supposed to be used as compressed elements in this design. A detail of the connection had to be designed in such a way that the tensile cables coming from different directions all met at the axis of the tube. De Vries worked on a connection involving wooden plugs and steel studs (see Fig. 6.130). The material tests and calculations performed on the paper tubes showed that the chosen type of tubes was not strong enough for such a structure and that it failed because the paper layers buckled and delaminated (see Fig. 6.130. However, if stronger tubes were used (made from virgin fibres), and if better glue were applied, it would be worth conducting further tests and verifying the potential of using paper tubes in tensegrity structures.

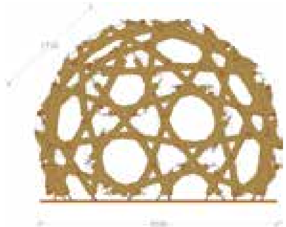


FIGURE 6.129 Drawing of the tensegrity dome

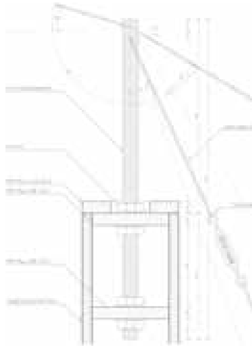


FIGURE 6.130 Detail drawing of connection

FIGURE 6.131 Paper tube compression/buckling test

The Dome of the Rings designed by Feng Liu and Melani Schafer was a double-layered structure composed of sliced paper tubes (see Fig. 6.132). The dome was 2.3 metres high and had a diameter of 4.6m. The proposed dimensions of the sliced paper tubes were 80mm (length), 300mm (diameter) and 10mm (thickness of the wall). The lower layer was connected with the upper one by inserting the paper tubes through the slots cut into the walls of the paper tubes (see Fig. 6.133). The paper tubes would intersect with each other at 40cm intervals. Then the sliced paper tubes would be connected by means of zip ties. The basic idea behind the dome was a 1v icosahedrons, which meant that the dome consisted of ten triangular flat panels which, after being bent, could be connected to each other (see Fig. 6.134). Connecting the panels would involve bending them in the positive and negative directions, so as to make the edges of the panels snap together. In order to achieve structural stability, the sliced paper tubes at the bottom would be relatively wide, while the ones at the top would gradually grow smaller. In addition, the rings at the bottom could be filled with plywood in order to make the tubes at the foot of the structure more rigid. Although the dome produced from sliced paper tubes of one single size would undoubtedly look beautiful, it was doubtful that it would function properly as an emergency shelter. Because of a lack of material, it was not possible to build a full prototype with a 1:1 scale.

FIGURE 6.132 Scale model of the Dome of the Rings

FIGURE 6.133 Intersection of sliced paper tubes

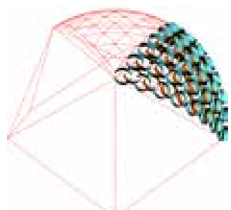


FIGURE 6.134 Single triangular panel projected on the 1v icosahedron dome

Elen Ordell and Davide Zanon designed a 'Structure That Shades Itself'. The aim of the design was to create a shading structure which, through proper use of the properties of the material, would span the distance and looked beautiful. The materials used for the project were 7.2mm double-layered corrugated cardboard, wood and glue. A paper rope was used to create a tension ring. The students opted for a geodesic icosahedron dome with a triangular division, but the straight members were replaced with spheres which were inscribed into geodesic dome triangles (see Fig. 6.135). Each of the spheres was composed of four circles cut from the plane surface. The circles interlocked in half-in-half connections. Each circle consisted of two layers of corrugated cardboard laminated together (see Fig. 6.136). Every sphere was connected to two other ones in the plane by means of slots in the circles. The whole cloud of spheres was placed on five pillars (see Fig. 6.137). One pillar was made out of four cardboard elements combined with nine other elements in the orthogonal direction. The pillars were installed on the base ring, made out of 20cm wide cardboard circles with a diameter of 4.2m. The Structure That Shades Itself was a delicate composition whose primary function was providing shade and looking beautiful. It could be produced from more resistant material and used outside, or alternatively, it could be connected with a lighting installation and hung from the ceiling. However, it did not work well as a dome, least of all a dome used in emergency situations.

FIGURE 6.135 Part of the prototype, realised with a scale of 1:1

FIGURE 6.136 Model and prototype of a single sphere

FIGURE 6.137 3D model of the whole structure

Mingjie Ning and Nick Vlaun proposed a shelter that could be folded up from a flat package by a twisting motion (see Fig. 6.138). This deployable disaster shelter was created in a shape similar to the shell of a land snail. The spiral-shaped floor plan had one entrance. The collapsible structural pattern consisted of vertical folds inwards and diagonal folds outwards. The so-called 'Shellter' had a height of 2 metres and was over 3 metres wide (see Fig. 6.139. The shelter consisted of 63 triangular panels (A, B and C) and additional top (E) and bottom (D) panels. The top E panels were connected with the A panels in order to preserve the shell shape, while the D panels were connected to the foldable floor plate. Some of the panels were detachable so that the package could be folded flat. These panels were connected with the adjacent ones by overlapping flaps that were connected by belts. A separate floor plate (which was pinned to the ground or loaded with heavy objects such as sandbags) was also connected with the shell by belts. The panels consisted of irregular triangles made out of two cross-laminated layers of 7mm corrugated cardboard. The triangles were connected by means of tape applied from both the inside and the outside. The panels were additionally covered with silicone-enhanced paper for waterproofing purposes (see Fig. 6.140). The 'Shellter' seemed to meet the requirements of the cardboard shelter. Its structural stability was proven by computer analysis, but some details needed further elaboration. The most dubious aspect of the design was the floor plate and its connection with the shell and the ground. Furthermore, the entrance to the shelter should be further developed to ensure that the conditions inside the shelter were comfortable. The structure itself could be transported in the form of flat packages, but the connections involving belts posed a risk of concentrated loads and water leakage.

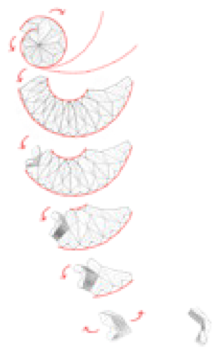


FIGURE 6.138 Folding motion of the structure

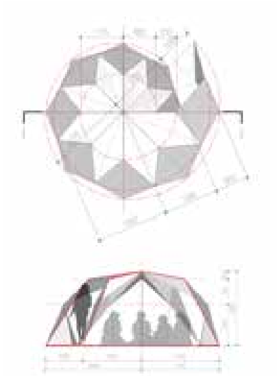


FIGURE 6.139 Plan and section of the 'Shellter'

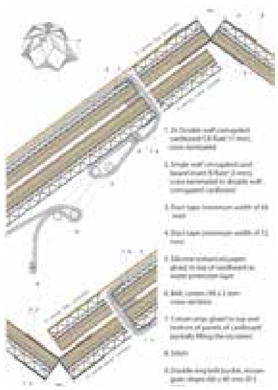


FIGURE 6.140 Detail of the connections between the panels

The dome designed by Mira Conci and Ayelt van Veen was composed of panels arranged in an alternating and cross-like design (see Fig. 6.141). The panels served as the structural elements of the dome. Each cross-like panel consisted of two flat boards with slots. Vertical and horizontal boards were inserted into each other (see Fig. 6.142). The boards were sandwich panels made of corrugated cardboard with Styrofoam in between (see Fig. 6.143). Additionally, triangular plates were connected with the cross-like panels by means of tie wraps in order to seal the space off from the external conditions. Although the dome looked impressive, it did not satisfy the requirements, which were to use cardboard as a building material. In order for this structure to work, the panels should be made of aluminium or plastic layers with thermal insulation material in between for greater stiffness. The connection between the panels caused point loads, which are hazardous when cardboard is used as a structural material. The openings in the panels would have to be covered with some extra (translucent) material. However, water would pose the greatest threat to the structure. Rain water would flow into the valleys created by the intersecting connections, thus damaging the material.

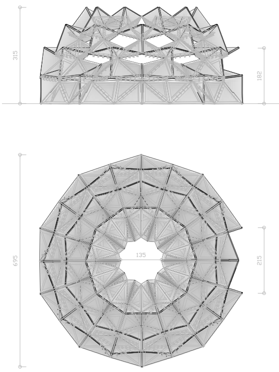


FIGURE 6.141 Side and top view of the dome

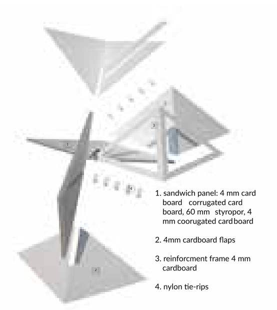


FIGURE 6.142 Exploded detail of the cross-like connection

FIGURE 6.143 Prototype of the cross-like connection

Rens Ottens and Floris van der Burght proposed an emergency modular building system of foldable components such as walls, floors and a roof, which would minimise the volume of the structure during storage and transportation. Each of the emergency units consisted of four panels that were self-supporting. The panels were connected together by hinges. After the unit was erected, the hinges were locked by means of a pin. The hinges also served as connectors between the single units. First and the last units of the row were closed off by a gable wall reinforced with diagonal bracing (see Fig. 144). Once the shelters had been erected, the wall, roof and floor panels were unfolded. Two motions were required to unfold the panels. The folded flaps were first rotated by 90 degrees, then folded back by 60 degrees. This movement allowed the inner flaps incorporated into the panels to open and lock. This is how the panels gained the required thickness and stability. The motion of the flaps of the panels was of the 'only-one-direction-possible' variety, which made the whole process quite simple. The authors called the principle behind their project 'movement from 1D to 2D to 3D'.

Although no full prototype was realised, the wall and floor panels were built and tested (see Fig. 6.145). As the creasing lines in the flaps of the panels had to be very precisely positioned and bruised, a special bruising machine had to be built first. There was no time for this, which is why no full prototype was created.

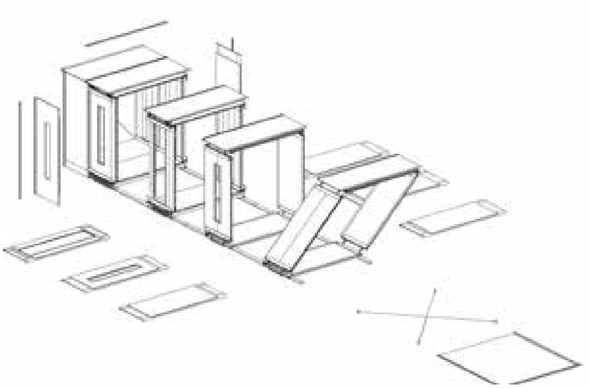


FIGURE 6.144 Building-up scenario

FIGURE 6.145 1:1 scale prototype of the floor and wall panels

The Outreach was an expandable shell shelter designed by Jik Mosch and Mitchell Mac-Lean. The design of each unit involved four shell segments of increasingly small sizes, which allowed them to be pushed into each other for storage and transportation purposes. When the Outreach was placed in the desired location, the shells were slid from each other to create a shelter with an area of approx. 14m^2 (see Fig. 6.146). Each shell segment was composed of primary and secondary structures and foundations (see Fig. 6.147). The primary structure was composed of corrugated cardboard arches, whose corrugation lines followed along the curvature of the arch. There were four arches in each of the shells. The arches were connected to each other by secondary structural elements – horizontal paperboard L-shapes. The L-shapes also served as shelves for additional thermal insulation. The arches had varying thicknesses, with the last arch of each segment overlapping with the first arch of the next segment. The overlapping arches were bolted together in order to stabilise the structure and keep the segments in position. Other structural parts of the shelter included the wooden floor and foundation. The floor and foundation of each segment consisted of two plywood boards that were hinged to the wooden box foundation. While the Outreach was inserted, the floor plates were put up in order to create enough room for the other shell segments. When the structure was opened, the floor panels were put in horizontal position and the floor legs were unfolded. The foundation boxes could be filled with material such as gravel or sand for better stability. The walls of the shell segments were covered by rolled-up paper. However , other cladding options were considered, such as pouring concrete over the exterior or cladding the shells with clay for better insulation. The first and last shell were closed off by gable walls with openings. The prototype of the structure was only partly executed. It was hard to evaluate the project on the basis of the work completed, because the most complicated parts, such as the connections between the segments or the outer layer of the structure, had not been completed (see Fig. 6.148).

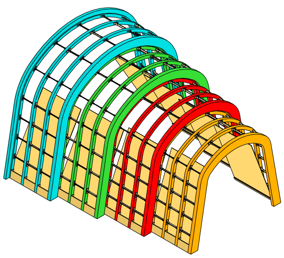


FIGURE 6.146 The structural parts of the Outreach

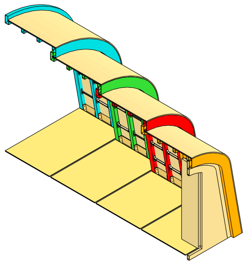


FIGURE 6.147 The Outreach section

FIGURE 6.148 Partly realised prototype

§ 6.3 Conclusions

The projects presented in this chapter, designed and executed in the form of prototypes, show different approaches to cardboard as a building material. Most of the projects realised had foldable structures. The paper-and-cardboard structures are reminiscent of origami folding patterns, and many students made good use of the flexibility of the material. However, folds also give rise to problems. Since the material used for these projects was not a thin, single sheet of origami paper, but rather thicker paper, the connections between the foldable elements required special attention. There were several types of connections between plates that ended up creating foldable structures. Duct tape and hinges (including a so-called 'live hinge') were the solutions used most often. Duct tape proved strong enough to be used in real situations, but the hinges proved to be a more risky proposition. First of all, connecting the hinge required screwing/bolting or gluing. Point connections involving bolts can easily damage paper or cardboard. As long as the elements are not too big and therefore lightweight, they can be folded without any risk of damage. Folding up big elements would result in significant bending moments at the connection with the hinges. Therefore, projects involving such hinges had to be limited in size and it would be difficult to make the folding parts bigger than just a few square metres. Another noticeable trend was structures composed of prefabricated components that were connected to each other by joints, mainly screwed or bolted to each other. Intersecting and sliding solutions were tested, as well.

If the projects were to be categorised by the structural system involved, the largest number of projects were shell-plate structures, followed by shell-strut systems. Other shell structures included hybrid solutions combining both plates and struts. In addition to systems whose structure consisted of a shell, columns-and-beams systems were used. The latter incorporated a structural system based on walls, floors and roofs made of plate.

The foldable structures had the advantage of quick erection and a relatively small volume when folded down for storage and transportation. Depending on the structural system used in these projects, the riskiest part was the stability of the structure after it had been unfolded. In some cases the material used seemed too weak to hold dead loads and loads caused by wind and snow. Some of these projects could be used as a temporary shelter which could be upgraded if necessary by pouring a concrete or resin layer on their surface. The inhabitants would not even have to leave the shelter for this. On the other hand, those projects that incorporated several individual components and were assembled at the building site proved more rigid and stable. Although their building process was more complicated and required the use of extra tools and sometimes specialist labour on site, the volume of the components in their packages was also minimised.

One aspect that had to be taken into account was that even if emergency shelters are built for several months or perhaps a few years, they may well be used for much longer than that. Therefore, it was crucial that the structures be safe and stable in the long term.

Most of the projects submitted were attempts at creating an emergency shelter, but there were several projects that did not meet the requirements of emergency architecture. Some of the projects seemed to revolve around the idea that a shelter was something that could be delivered at an emergency site quickly, while others would require a fair bit of time to be erected. Most of the proposals assumed that the structure would have inhabitants, but there were also interesting examples of structures that could serve as public spaces, retail utility units or hospitals. Ideally, a structure would be able to be adapted to different types of use.

The type of material most commonly used for the production of the prototype was corrugated cardboard. This material is produced in big quantities, therefore cheap, and can be used in construction. The downside of corrugated cardboard is its anisotropy. Corrugated panels are weak when subjected to forces perpendicular to the direction of the corrugation. Cross-lamination of the corrugated cardboard plates may mitigate this problem. However, corrugated cardboard is weak when forces are applied in the perpendicular direction to its surface. Fifteen out of the nineteen projects presented at the end of the course incorporated corrugated cardboard, mainly because it is widely available and cheap. However, when forces are applied perpendicular to the surface, honeycomb panels are a better solution than corrugated cardboard. In those projects that involved floor panels, cardboard honeycomb was the most used material. The floor panels were covered with additional material such as plywood or OSB panels to prevent point loads and to spread the forces more evenly on the surface. Both paper tubes and cardboard L- and U-shapes were used in the shell-strut and columns-and-beams systems submitted. Paperboard and paper were used in three projects. In the case of the SCOLP project, the difficulties associated with cutting and laminating the paperboard connections were too complicated for mass production, although the project showed great potential.

As mentioned before, the types of connections used between the various structural parts depended on the structural system and erection method used. The foldable structures featured elements connected by duct tape, textile or hinges. The hinges were bolted into the material. Projects involving columns and beams used joints made out of wood. Such joints were connected with the strut elements by means of glue, nails or screws. One exceptional solution was the use of cardboard as a joint member. In the SCOLP project, the paper tubes were connected by laminated connectors made of paper board and locked into each other by cardboard wedges. The Curved Fold Dome used corrugated cardboard members, but the members were connected to the struts by means of zip ties, which caused the material to tear.

Intersecting structural elements were used in the Waffle Dome and Dome of the Ring projects and in the dome designed by Conci and Van Veen. This type of connection required extra reinforcement in the form of an outer layer that would keep the elements in place, or bracing, or additional connections between the intersecting parts. Another type of connection that was used was a post-tensioned connection between cardboard hexagons and paper tubes in the HEX Shelter project.

Post-tensioning and connections involving wooden joints were the most durable and the most consistent with the properties of the material. These methods should be considered in the further development of emergency shelters.

A wide range of ideas were presented with regard to methods to connect the structures to the ground. Some projects included platforms, which were simply positioned on levelled ground. Such platforms were often designed as sandwich panels composed of wooden plates (plywood, OSB) and honeycomb panels. While honeycomb panels could work as a form of thermal insulation, they should not to be used in direct contact with the soil unless they have been thoroughly impregnated and waterproofed. However, even after impregnation, cardboard can be easily damaged by capillarity, as happened at Hualin Primary School. Therefore, designs that involve cardboard being used in direct contact with the ground should be avoided.

There were also several projects that used boxes (made of wood or cardboard) as a basic structural element. These boxes could be filled with gravel or sand. However, as mentioned above, cardboard is not suitable for such solutions.

Anchored foundations following the platforms were most commonly used in dome-like structures. Out of all the proposed solutions, the ones that should be taken into account as functional and safe in relation to the material used are those in which structural elements (timber and cardboard) were kept away from the ground. The Papyrus Hospital System and Profile: Select Your Needs are projects in which a suitable foundation in the form of concrete blocks, paper tubes filled with concrete or other solutions (like plastic containers or ground screws)might be successfully applied.

One of the key issues in the design of emergency structures is thermal insulation. As demonstrated in Chapter 5, emergency structures are needed in every kind of climate. Therefore, we must design solutions specific to a certain region or propose a universal system that can be adapted to different climates. Most of the projects submitted in the course were designed for hot climates. Several of these projects took into account temperature changes, insulation and annual rainfall. The most desirable solution would be a universal structural system which can be adapted to local circumstances by means of different types of the panels. This idea was presented in the Umbrella Shelter project and the Profile: Select Your Needs project, in which two different types of envelope were proposed. A project with a foldable mechanism, which incorporates structure and envelope elements into one system, will not meet this requirement.

Although impregnation is a crucial aspect of building with cardboard since it protects structures from moisture, water, fire, insects, etc., the prototypes presented in the course mainly focused on geometry, structural system, the type of material used and its composition, storage, transportation, production and construction issues. Impregnation was not taken into account here. On the other hand, the process of designing and prototyping was an important part of the assignment. Individual designs that were later merged into group projects were first worked out on paper by means of sketches and brief descriptions of proposed systems and solutions. Then computations were carried out, while at the same time scale models and mock-ups of parts of the structures were created. The physical models and mock-ups allowed the students to investigate details of the structure, such as its stability or the connections between the various elements, and also helped them avoid structural problems in the early stages of the designing process. In some cases material tests had to be conducted in order to gather fundamental knowledge of the material and its behaviour, which was then included in structural calculations. The final part of the process – constructing the prototypes – was the ultimate verification of the architectural solutions implemented. The prototypes showed what the actual construction process might look like, what kind of tools could be used and how many people could erect a shelter in any given amount of time. It also brought production processes of prefabricated components or shelters to life for the students. The prototypes that were built allowed the students to assess what was possible in terms of storage and transportation.

Some of the projects presented at the end of the course were very useful and had significant potential for further development. Even if they were unsuited to being used as emergency shelters, they could be treated as interesting structures that could be used for temporary events, expositions, festivals, etc.

For the sake of further research that will come up with the optimal solution for emergency structures made of cardboard, the following performance indicators drawn from realised prototypes should be taken into account, developed and implemented in future projects:

- Function-focused design – the design must be simple so that regular people without specialist knowledge can assemble the structure.
- Easy storage – the volume must be minimised to allow the structures to be stored in a warehouse in large quantities.
- Easy transport – the elements and components of the structures should fit into a lorry or shipping container. They should be folded or individually wrapped in a way that allows large numbers of shelters to be transported, without any wasted space caused by half-empty packaging.
- Lightweight elements, components or entire structures in the form of prefabricated products – the products should be able to be moved from the truck and carried at the building site by hand. This will reduce the costs of transportation and prevent special tools or machines from being needed on site.

- Simple structures – the more basic the structure, the more likely that people without much knowledge of construction and without specialist equipments will be able to erect it

- Height – the height of the shelters should not exceed five metres, so that no additional equipment will be needed to erect them.

- The structure could be composed of integrated load-bearing elements or have the form of frame structure – i.e, a load-bearing system filled with thermal insulation panels. The first option, however, reduces the likelihood that the shelters will be able to be used in different climatic conditions.

- The floor panels should be kept away from the ground, thus minimising direct contact between the cardboard elements and water, which will in turn reduce capillary action. The possibility of creating of an Under-Floor Air Distribution (UFAD) system could be explored, too.

- In order to minimise ecological damage caused by the shelters, the Light-Touch-to-the-Ground approach should be adopted. In general, this involves the use of pile foundations, ground screws or other solutions for raised floor slabs.

- The structure should be designed as a temporary structure, but it should come with a five-year warranty.

- The structure should be created in such a way that the parts of the shelter can be replaced, retrofitted, fixed, improved, rebuilt or rearranged, without the inhabitants having to move out.

- The structural system should be universal and flexible, which means that it allows manufacturers to produce smaller and bigger units from mass produced paper elements

- The shelters should be able to be clustered in bigger groups – for example, in the form of row houses, courtyard houses or a nested arrangement of units.

- The shelter should have a neutral shape that will be acceptable to inhabitants of different backgrounds. Possible customisation is advisable, for instance in the form of printed colours or elements added to the façade.

- The shelters should have a basic shape with straight vertical divisions which allows the inhabitants to use commonly available furniture.

- The material and impregnation methods used should allow down-cycling or recycling of the material after the lifespan of the shelter.

- The amount of waste produced by production, construction, usufruct and demolition should be minimised.

The above indicators will be used as aspect analysis or input data in further research by design, development and prototyping of transportable emergency cardboard houses.

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7 TECH. Transportable Emergency Cardboard House

FLe^{2}XARD the way to go ! [1]

§ 7.1 Introduction.

TECH: Transportable Emergency Cardboard House was a project involving shelters for people in difficult housing situations.

The TECH project was based on previously conducted research. The fundamental research on paper, presented in Chapter 2, focused on the material itself, its mechanical properties, its chemical and physical structure, its production methods and elements mass-produced by the paper industry. Next, research was conducted on the applications of paper products in design and architecture. The sixteen realised structures, in which paper was employed as a building material, were analysed for their structural systems, the paper products used, the connections made between the structural elements, the connections with the ground, the impregnation methods deployed and the design and implementation processes involved. Lastly, the paper emergency structures realised in the form of prototypes, in which different paper products and structural systems were examined, resulted in the further guidelines for paper emergency shelters presented in Chapter 6.

A column-and-beam structural system was chosen as it is a simple system that can be built quickly without professional construction workers and without special equipment and tools.

The chosen structural system consists of slender elements in the form of columns and beams. To build that system cardboard U- and L-shapes were used.

Paper tubes, which were an alternative for the U- and L-shapes, are hard products to connect to other types of building components due to their geometry. Either the paper tubes are placed inside a building, taking up space that may already be limited, or they are incorporated into the envelope, where they are subject to external conditions. For this reason, it is more practical to use paper products such as L- and U-shapes as structural elements.

The TECH project was targeted at forcibly displaced and homeless people. Please refer to Chapter 5 to read more research on motivations and guidelines for emergency and relief shelters.

The number of forcibly displaced people was estimated to be 65.6 million at the end of 2016. [2] Forcibly displaced people are people who had to flee their houses and cities because of persecution, conflicts, generalised violence or human rights violations. Three different categories of forcibly displaced people can be distinguished:

- Internally displaced people (IDPs)
- Refugees
- Asylum seekers

The number of homeless people living rough or in shelters or hostels provided by aid organisations in developed countries was 1,777,308 in 2015. [3]

Asylum seekers who come to Europe but are not granted refugee status run the risk of becoming homeless.

Each of the aforementioned groups requires different types of support, including housing. As far as accommodation is concerned, the support they receive may come in the form of mass shelters, dispersed settlements, hosting families or spontaneous or planned camps.

TECH is an acronym for Transportable Emergency Cardboard House. The designations 'TECH 01', 'TECH 02' and 'TECH 03') refer to successive versions of the project where structural parts and building components and impregnation techniques were improved.

There are three generations of TECH. While TECH 01 was prepared as an unbuilt project and only the prototype of the wall structure was executed, TECH 02 and TECH 03 were executed as 1:1 scale prototypes. TECH 02 was exhibited at the campus of TU Delft's Faculty of Architecture for several days. TECH 03 was built in September 2016. Since then it has been at Wroclaw University of Science and Technology's

Faculty of Architecture, where it is exposed to natural conditions and changing weather conditions.

In general it can be said that TECH is a group of solutions for emergency and temporary housing, which can be used to serve people in difficult housing situations. However, TECH 03, also known as 'the House of Cards', may also serve as a commercial structure. It can be used as a garden or summer house, as an extension of existing buildings, shed, temporary office building, hotel room or storage space for events like trade fairs, exhibitions, major sporting events, etc. TECH 03 was designed to meet European architectural standards, especially with regard to thermal insulation.

This chapter is mainly concerned with the structural system of the TECH solutions, as well as the paper products used as building components, the usability and feasibility of the shelters and their production methods.

§ 7.2 Design methodology

The process of designing, researching and developing emergency shelters made out of paper elements and components was divided into two phases (see Fig. 7.1). The first phase consisted of fundamental and technical research, which also encompassed material research, an examination of the opportunities and risks presented by the use of paper products in design and architecture, and research on the social aspects of emergency and relief shelters. The second phase (practical research) included research by design, engineering, prototyping and tests conducted to tests on mechanical properties of the material as well as impregnation methods.

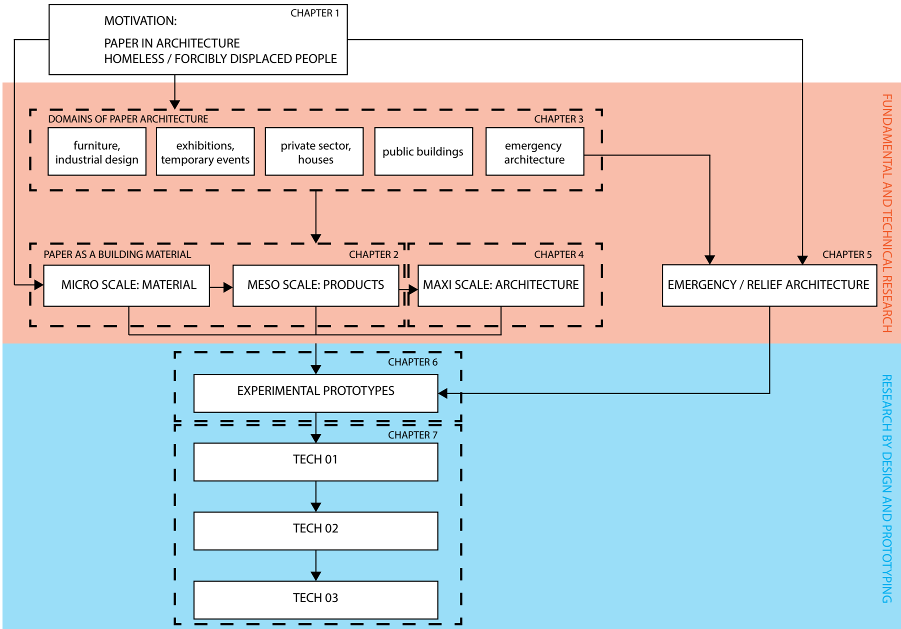

FIGURE 7.1 Research scheme

The basic motivation for the research and development undertaken as part of this project was the hypothesis that paper is a suitable material for emergency shelters on account of its cost-efficient production, availability, eco-friendliness and structural and mechanical properties.

The main goal of the process was to develop a product which would satisfy all the requirements for emergency situations, and would provide the market with an adequate emergency shelter that would improve the living conditions of victims of natural and man-made disasters and homeless persons.

The project was carried out in accordance with the Methodology of Product Development in Architecture proposed by Mick Eekhout. [4] Product development as described by Eekhout is based on organograms. Organograms can be used as a holistic approach to three different types of building products: standard products, system products and special products.

Standard product – standardised and produced independently of the designers. The architect only gets to decide how to position the product in space (topology) – i.e., tiles, bricks, bolts and nuts.

System product – developed as an integral system and built from functional elements and components. A system product can be applied to different projects. Its colours or dimensions may change, but the technical core of the system will never change. System products are intended to be applied to different projects.

Special product – a product or component particularly designed for a certain building project. Sometimes special products are made up of standard and system sub-products.

There are three main types of products, as well as four transitional types:

- **STANDARD PRODUCTS**
  Systematised standard products
  Standardised system products
- **SYSTEM PRODUCTS**
  Special system products
  Systematised special products
- **SPECIAL PRODUCTS**

An architect has 100% influence on special products and 0% influence on standard product. For producers it is the other way around.

Cardboard products like paper tubes, corrugated boards, honeycomb panels and U- and L-shapes are typical standard products produced in large quantities by factories. The exact quantity depends on the factory and the type of machinery used. Many factories produce thousands of tonnes of corrugated cardboard per day.

As TECH is a structure consisting of several components which are in turn composed of standard products, it can be assumed that TECH is a special product.

Organograms are a reflection of the sequence of activities undertaken during the design, research and development process. They are used as a model for smooth designing and developing processes (see Fig. 7.2). Organogram describe sequences of serial processes (one after the other) or parallel processes (one next to the other – concurrent engineering). The organogram used on the TECH project involves eight steps.

The first step is defining the Evaluation Criteria. This helps define exact expectations and when they are expected to be fulfilled. It is possible to return to this stage several times during the process. If no criteria are defined at this stage, researchers will not know if the process, after having gone through several steps, is correct, or whether it will lead to the desired results.

The second step is Aspect Study. During this phase the main problem is sub-divided into several sub-problems. Such problems may be considered autonomous or partly autonomous aspects of the subject, so they can be studied separately. The separated aspects are later combined or integrated into the clusters.

Each cluster of aspects consists of four steps:

- Analysis
- Brainstorming
- Ideas
- Synthesis

The concepts of the various aspects are then combined into a complete product concept.

Once a product concept has been drawn up, it is a time to decide if the resulting product concept is technically feasible. The next step cannot be taken until the feedback is completely positive.

In the organogram presented below, the evaluation criteria and aspect study and analysis were combined into five clusters. The criteria were analysed and studied during the research on material and emergency architecture. Then they were turned into the product concepts and prototypes described in Chapter 6 (called 6.2 CS in the organogram). Next, based on previous research and prototyping, the criteria and aspects were studied and analysed again, which resulted in the concept of TECH. TECH 01 (7.3 TECH 01) was analysed and design of the structure was prepared. Additionally the prototype of the wall component was built. The next generation of the building, TECH 02 (7.4 TECH 02), based on the further analysis of the primary concept design of TECH. After the construction of the TECH 02 prototype, and the evaluation of its structure and details, the final version (TECH 03) was prepared (7.5 TECH 03).

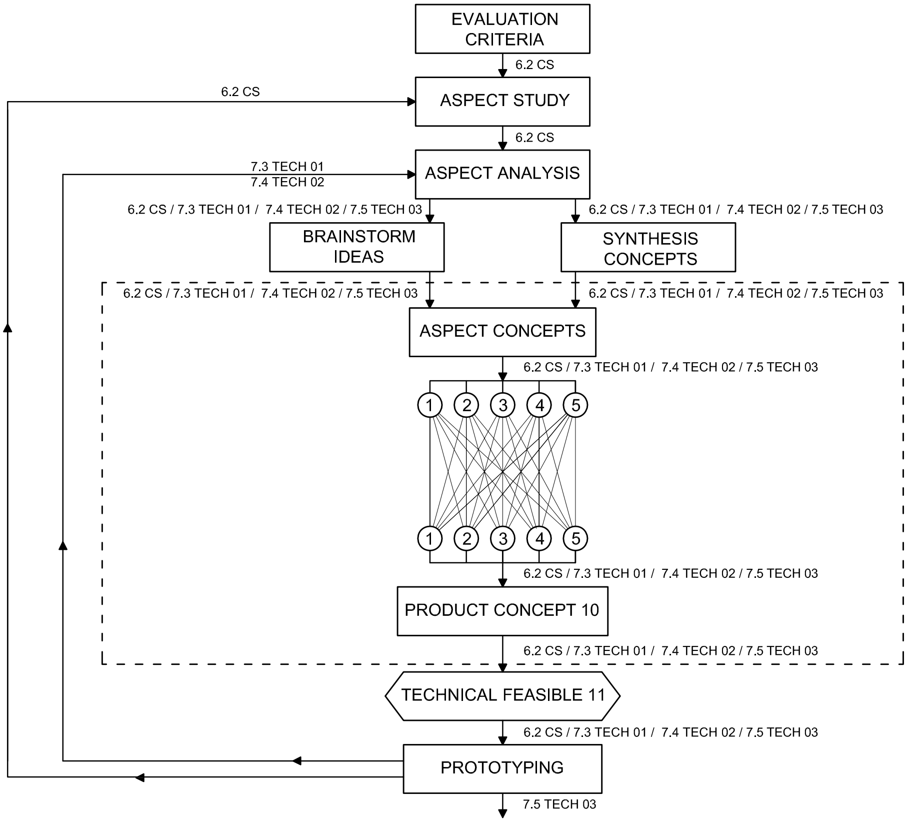

FIGURE 7.2 Organogram adopted for the TECH project

During the work with the organogram, certain sequences create four clusters of related activities:

- Objective / goal
- Analysis and synthesis of aspects
- Product concept
- Evaluation and feasibility

The order of these clusters cannot be altered, but there is a certain amount of freedom within the clusters: the individual activities can be gone through serially or in a parallel manner. The architect or designer has no influence on the standard products. The only thing s/he can do is decide whether or not to use a certain product.

The organogram for products in architecture consists of five phases:

- Design concept
- Preliminary marketing
- Prototype development
- Final marketing
- Product manufacturing

TECH followed the first three steps.

The preliminary marketing was presented in chapter 5, where the 'target group' and the scale of demands were described.

Specific goals for the project included the following:

- Design parameters (area, dimensions)
- Spatial planning on site
- A flexible structure in terms of layout and further extension
- Project and production of building components and elements
- Building process

In order to achieve goals in architectural projects, several steps have to be undertaken and a process strategy must be adopted. The main steps in the design, research and development strategy are:

- Setting the criteria and aspects of the project (requirements and functions)
- Setting the design objectives
- Preparation of the concept design – project concept
- Technical and material solutions and feasibility
- Prototyping
- Evaluation

These above steps must be evaluated and assessed to ensure that a project has the desired results. If the evaluation is not positive, all parties involved must take a step back and rethink the process.

The criteria and aspects for the Transportable Emergency Cardboard House project were divided into five clusters:

- Design requirements and functions
- Material aspects
- Technical solutions
- Potential for production
- Implementation of the product

DESIGN REQUIREMENTS AND FUNCTIONS	MATERIAL ASPECTS	TECHNICAL SOLUTIONS	PRODUCTION	IMPLEMENTATION
Addressed 'target' group	Elements mass produced by paper industry	Building components and elements	Production process	Storage
Function-focused design	Efficient thermal and acoustic insulation	Structural system:flexible, quick	Costs of the shelter	Transportation
Neutral	Impregnation methods	Connection between the elements and components		Construction (weight of the elements, equipment required)
Size of the shelter	Minimising the ecological burden	Connection with the ground		Simple construction process (no professionals required; quick erection of building)
Flexible layout				
Special layout				
Lifespan				

TABLE 7.1 Five clusters of criteria and aspects for the Transportable Emergency Cardboard House project

Design requirements and functions

TECH is an emergency shelter geared towards people affected by natural and man-made disasters and to homeless people. It is particularly geared towards forcibly replaced people, who are one of the main subjects of this thesis, along with homeless people in developed countries. Both groups were specifically described in Chapter 5. Since this group of people is large and diverse, the shelter should allow for adaptations to local natural and cultural conditions. As the shelter should first and foremost fulfil people's physiological and safety needs, the design should be function-focused. It is advisable to create shelters with simple shapes and straight walls, which will allow users to outfit them with commonly available furniture. However, the shape and structure of the design should allow further development and enlargement of the shelter in the future. The appearance of the shelter should be modest and neutral, so that it will be suited to various cultural backgrounds. Furthermore, the design must involve building components whose appearance can be modified according to local conditions and traditions. Such modifications may be made by physically modifying building components or by means of printed outer layers to be put on the building components. For example, shelters designed for different regions with different cultural backgrounds may have different types of windows or protection from the sun. In European regions, rectangular shapes are most popular, while in Asian countries the dominating element is a circle, and in Middle Eastern countries it is an octagon. The various versions of Shigeru Ban's Paper Log House are a good example of a shelter adapted to different cultural and climatic conditions (see Sections 4.3.4 and 5.5.5). According to the typology presented in Chapter 5, TECH should be designed as a temporary shelter or temporary house (see Section 5.4). This means that TECH could be used for months or years and its lifespan should be assumed to be one to five years, with a possible extension.

TECH is a product that can replace the standard UNHCR family tent. Therefore, its size should be similar to the typical size of UNHCR's tents. The size of UNHCR's tents is based on the assumption that a family consists of five members, and the minimum requirements are 3.5m^2 per member of the family. Therefore, tents with an area of 17.5m^2 are most common. However, families come in different sizes. For this reason, different sizes should be available, and there should be a possibility of clustering several shelters in the event of a bigger family or a need for another function, such as education or healthcare. One of TECH's main goals was to provide a form of shelter that can be easily modified, depending on how much space the users need. The structure of the shelter should allow for rearrangement or reconstruction in several different configurations. Therefore, the structural system should be flexible and consist of elements and components that can be changed, depending on the required layout.

Material aspects

The goal for TECH was to produce a lightweight, low-cost and eco-friendly shelter that would provide sufficient comfort to its inhabitants.

In order to achieve this goal, the author of this dissertation researched products mass produced by the paper industry. As described in Chapter 2, this research mostly comprised five categories of products, which are produced in large quantities: paperboard, paper tubes, corrugated cardboard, honeycomb panels, L-shapes and U-shapes. Each of these products has its own characteristics and can be used as part of a different type of structure. Paper tubes and L-shapes (or U-shapes) can be used as part of frame structures, while corrugated cardboard and honeycomb panels can be applied as filler for the envelope of a building. When paper tubes are used as structural elements, they are hard to combine with other building components, such as walls, because the circular shape of the tube is at odds with the linear shape of the wall. Paper tubes can also be used as elements of a wall, as in the Paper Log House (see Section 4.3.4). In such situations, paper tubes are placed next to each other. However, this solution results in thermal bridges and loss of energy at the connections between the tubes. Due to their shape, L-shapes and U-shapes are much better suited to being used as a frame structure connected to the walls and roof. The mechanical properties of L-shapes and U-shapes were proved by material tests (see Appendix 1), and their usability in architectural structures was proven in previous attempts and prototypes (see Chapter 6). For this reason, they were the author's material of choice for the frame structure. Wall and roof panels can be made of corrugated cardboard or honeycomb panels, or both. From a thermal insulation point of view both materials (corrugated cardboard and honeycomb panels) show a relatively high level of insulation. The honeycomb panels should not be thicker than 25mm to let the air pockets create insulation cells filled with air.

TECH's floor can be made from both paper elements and timber elements. However, the latter is more suitable in structures that are supposed to have a long lifespan.

Given the enormous number of people who need a temporary shelter or temporary house, the ecological impact of the chosen materials and the way in which they are to be processed are important matters for consideration. While paper can be easily recycled, it is also vulnerable to water and moist. In order to minimise the ecological burden, the material should be impregnated against water and fire in a way that allows further recycling. This can be done by applying the layer of impregnation on the surface of the building component by means of lamination. The laminated layer can be later ripped off, after which the rest of the material can be recycled. Another option is to use a type of varnish that will not prevent the material from being recycled. Impregnation methods should be further researched by a specialist in the field of chemical engineering and paper production.

Technical solutions

Out of the three most common structural systems: rod system, panel system and shell system, the first two are the most suitable for use in temporary shelters and housing. The panel system, which is quick in use and has a small volume when folded down, proved to be very limited in terms of functional flexibility, potential for rearrangement and structural stability. In a panel system the panels should be integrated with load-bearing elements. If a frame system is used it should be filled with insulating panels. The latter solution allows alternating between panels, which means the structure can be adapted to different climatic conditions. The structure should be created in a way that allows it parts to be fixed, replaced or renovated. The shelter should be properly insulated from the ground. This can be achieved by means of a good insulation layer and by elevating the shelter from the ground. In this case an under-floor air distribution system (UFAD) would be possible. The connection between the building and the ground, by means of concrete feet or ground screws, will allow for UFAD and will minimise the ecological imprint on the terrain. TECH should be composed of prefabricated building elements and components. If they all have similar dimensions, the shelter will be competitively priced, and a flexible layout will be possible. The connection between the elements and components should be easy to allow the shelter to be erected quickly, even by non-professional construction workers.

Production

TECH is a shelter made out of paper elements and components. This means that the paper industry will be involved in its production and that mass-produced products are used. L-shapes and U-shapes, which will be used as a structural frame, are available all over the world, as are corrugated cardboard and honeycomb panels. Such products are staples in the paper industry and are mostly used for packaging purposes. It vital that certain types of paper products be used, and that their production processes be taken into account. The structural elements of the shelter can be made out of recycled paper, but it is advisable to check the mechanical properties of said paper. The mechanical properties of paper depend on the source material (pulp) and the paper production process used. This is explained in more detail in Chapter 2. The strategy for TECH is to use mass-produced paper products that will be sent to a production factory. The factory will then combine the standard products into building elements and building components. Components such as doors, windows, ventilation grids, ventilation shafts and electrical installations will be ordered from external factories. Where necessary, the products will be impregnated, then combined into building elements or building components. The production process needs to be carefully thought out and planned so that a large number of shelters will be able to be produced. Building components (i.e. the floor components, walls and roof) should be produced parallel, so that the speed of production will be increased and the quality of the components can be checked at the end of the production lines. The costs of the shelter depend on several features, such as its size, structure, floor, connection with the ground, thermal insulation and quantity of the units. However, the final price should be close to or not much higher than the price of existing solutions for emergency shelters.

Implementation

Emergency shelters, as well as temporary shelters and temporary housing, are often needed in large numbers, due to the number of people affected by natural or man-made disasters and the need for an immediate response in the event of a disaster (see

Chapter 5). Therefore, TECH should be produced in large numbers, as well. In order to allow for immediate demand, the building elements and components should be easy to store. This means that the size of the individual building component should be optimised so they can be kept in warehouses without taking up too much room. The size of the components is a factor in transportation, as well. Since transportation costs sometimes exceed the costs of the shelter itself, a careful transportation strategy must be drawn up, allowing various modes of transportation (e.g. shipping containers) to be used to their maximum capacity.

The size and weight of the various building components should be minimised, so the structure can be erected without a need for specialist equipment and the components can be moved on the building site by human power. The maximum weight per person on the building site should not exceed 25 kg. Construction of the shelter should be easy, thus allowing non-professional construction workers to erect the buildings quickly.

The aforementioned criteria and aspects will be now incorporated into the proposals for the Transportable Emergency Cardboard House.

§ 7.3 TECH 01 - unbuilt

Author: Jerzy Latka
Year: 2014
Location: Iraq
Area: 17.4m^2 (size: M)
Lifespan: Temporary (estimated lifespan five years)
Type: Emergency / temporary shelter

The TECH 01 is a lightweight cardboard structure designed to be used as an emergency or temporary shelter for refugees and victims of natural and man-made disasters.

The aim of the project is to create low-cost, easy-to-transport, lightweight and eco-friendly structures that may serve as houses or educational or medical units. TECH

01 will replace the typical tent structures provided to refugee camps by UNHCR. It will provide people with a higher degree of comfort, including privacy, safety and indoor thermal conditions.

§ 7.3.1 The design objectives

The design objective of the TECH 01 is to provide a low-cost house that can be mass produced and delivered to the desired location in a shipping container. The house should be easily assembled by non-professionals, without any need for specialist tools that may not be available at the refugee camps. The structure should consist of several elements that can be delivered in a twenty- or forty-foot shipping container. The elements should be lightweight so the future inhabitants can assemble them themselves, using nothing but manpower. The building process should be sufficiently easy to be carried out by non-professionals, possibly under the supervision of volunteers.

The floor area of the house is approximately 17.5 m^2, which is the minimum required area for a consisting of five persons. Therefore, the minimum floor area for one person is 3.5 m^2. However, the house could be designed in two different versions, one being a bit bigger (17.4m^2) and the other being a bit smaller (12.7m^2). TECH 01 can be erected in any configuration the users need: in the form of single units, row houses or a group of houses (nested). Alternatively, several TECH 01 units can be combined to form a long building used for education or healthcare purposes.

§ 7.3.2 Project concept

TECH 01 is a one-room temporary shelter. It has a rectangular shape, whose outer dimensions are 3,740 by 4,950 millimetres, and whose usable area is 17.4 m^2 (see Fig. 7.4). The shelter has three openings: one door (1,940x800mm) and two windows (920x920mm). Depending on the layout of the plot, the house may be connected to a sanitary unit by means of a second door in the back wall. The doorway and windows are in the short walls (front and back walls). No openings will be created in the long walls to enable alignment of the houses in a row. The foundations of the shelter may take the form of concrete blocks, made on site by filling the provided paper tubes (with a diameter of 300mm) with concrete on levelled ground, covered with a plastic sheet.

Alternatively, the building may be anchored to the ground by means of ground screws. The height of the house is 1,920mm at the lowest point (the connection between the roof and the walls), and 2,300mm at the highest point (the ridge) (see Fig. 7.4).

The houses may be delivered in a range of colours to help the users identify their own houses.

The project was designed with a particular group of users in mind: Iraqi and Kurdish refugees. The average male in this group is 1.65m tall. [5] Therefore, the various components of the house, such as doors or walls, did not have to be as tall as they would have been in Europe.

The size of the building elements and components is determined by packaging and transportation requirements. The houses were intended to be sent to the site in a shipping container. As mentioned above, two types of containers were taken into account. Ten units of 12.7 m^2 and six units of 17.4 m^2 can fit into one forty-foot container (2,300 by 12,000mm). The largest elements of TECH 01 are its roof plates, whose maximum dimensions are 2,270 by 5,900mm. As a result, the plates fit into a forty-foot shipping container. The roof plates for a smaller unit have a maximum length of 5,700mm, which means they can fit into a twenty-foot container (see Fig. 7.3). After unloading, the container can be shipped back or used as a sanitary or kitchen unit or other facility by the aid organisation running the camp.

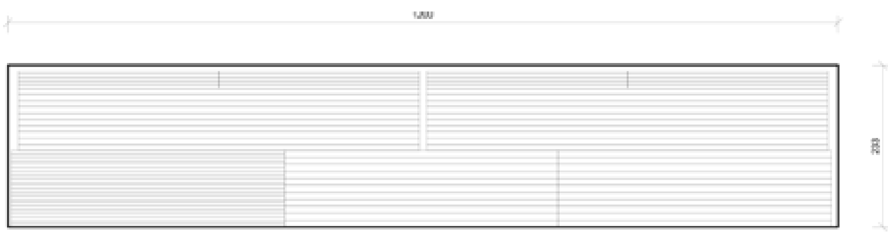

FIGURE 7.3 Arrangement of the TECH 01 11,0 m^2 components in 40’ shipping container

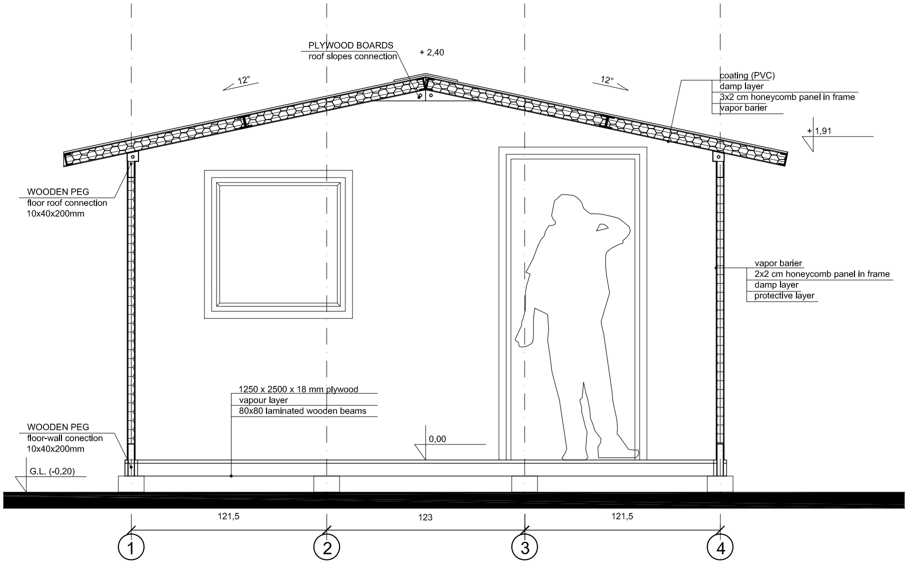

FIGURE 7.4 Tech 01 section

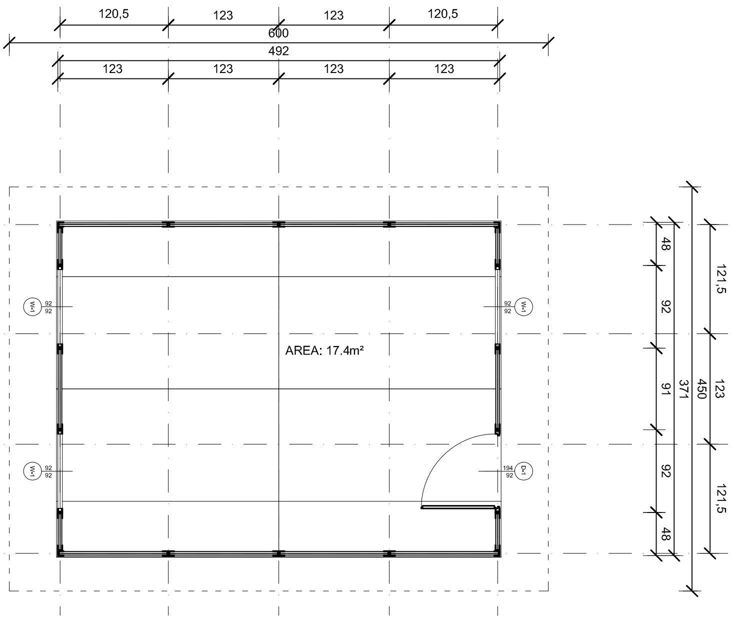

FIGURE 7.5 TECH 01 floor plan

The TECH 01 is designed in several components, which can be arranged in different setup. It is possible to make some variation in the spatial arrangement of the structure. Components in form of wall panels, floor and roof can be prepared in advance in factory and depending on the need, can be picked up like IKEA furniture packed in the boxes and combined together. Floor elements and roof panels stays the same. Therefore, the structure can be built as a single housing units or in a row, to serve as a row houses or as an educational or healthcare units (see Fig. 7.6 and 7.7).

FIGURE 7.6 TECH 01 Housing units

FIGURE 7.7 TECH 01 School

§ 7.3.3 Technical and material solutions

TECH 01 consists of three types of components: floor components, wall components and roof components.

Floor – made of impregnated wooden beams (80x80mm) covered with 18mm thick impregnated OSB or plywood board.

Short walls – composed of impregnated cardboard U-shape frames filled with two cardboard honeycomb panels with a thickness of 20mm each (see Fig. 7.8 and 7.9). Honeycomb cardboard panels are to be ordered from an external factory, and must be made of Kraft liner paper. The walls are covered with a vapour barrier on the inside and with a protective waterproof layer on the outside. Wooden joint elements are integrated in the wall panels which can be directly connect to the floor and roof components. The short walls are composed of five panels. One of them includes door and three panels include windows. Each wall is delivered as one integrated component.

Door D-1 – a pinewood frame with a lightweight wing. The wing of the door is composed of two plywood boards filled with a 20mm honeycomb cardboard panel. All doors come with handle hinges and a lock. The doors come in different colours.

Window W-1 – pinewood frame window, filled with 2mm Plexiglas, single glazing. The window comes with a handle and hinges.

The doors and windows are to be ordered from an external factory ready to be installed in the walls.

Long walls – composed of impregnated cardboard U-shape frames filled with two cardboard honeycomb panels with a thickness of 20mm each. The honeycomb cardboard panels are to be ordered from an external factory, and must be made of Kraft liner paper. The walls are covered with a vapour barrier on the inside and with a protective waterproof layer on the outside. Wooden joint elements are integrated into the wall panels so that they can be connected to the floor and roof. The two long walls of each unit are composed of four panels measuring 120cm each.

Roof – composed of two panels put together on the building site and placed onto the previously erected walls. Each panel is built out of three layers of cardboard honeycomb panels in a cardboard U-shape frame. The roof panels are covered with a vapour barrier on the inside and with a protective waterproof layer on the outside. Wooden joint elements are integrated into the roof panels. They are used to connect the panels to each other and to the walls. The roof pitch is twelve degrees, and its eaves are 40cm on the long side walls and 42cm on the short side walls.

Ventilation is provided by ventilation opening in the gable walls just under the connection between the two roof panels on either side of the house.


FIGURE 7.8 TECH 01 - wall component prototype


FIGURE 7.9 TECH 01 - wall component prototype front view

TECH 01 was designed to be an easy- to-transport, lightweight and easily erected emergency shelter. Composed of simple components, it can be erected by the future inhabitants (i.e., non-professional construction workers) with the help of volunteers. This method, which is called a self-help or mutual-aid programme, was successfully used by organisations such as Habitat for Humanity, Voluntary Architects Network or government programmes in Puerto Rico in the 1950s and 1960s. [6] Obviously, this method only works if the design of the structure is clear and easy to understand. Furthermore, each component must be lightweight so that the whole structure can be erected without any heavy equipment.

Once the components have been unloaded from the shipping container, the first thing to do is to prepare the ground. Once the ground is level, the following steps must be taken (see Fig. 7.10):

- Foundation – several methods are available to lay foundations, depending on the type and hardness of the local soil. If the soil is hard, levelling is required. Then plastic foil is placed on the ground, with the floor components on top of it. The floor components are connected to each other by means of bolts or screws. If the soil is softer, ground screws can be used to level the ground and to increase the distance between the ground and the floor, which will stop water from damaging the floor components and will enable the installation of an UFAD (under-floor air distribution) system. Alternatively, holes can be dug into the ground and filled with paper tubes with a diameter of 20cm and filled with gravel and concrete. The floor components will then be installed on the resulting paper-tube pillars.

- Once the foundation and floor have been set, the wall panels can be plugged in. As the first prototype shows, each wall panel has two wooden pegs that fit into the holes in the floor components. Subsequently the wall panels are screwed to the floor components and connected to each other by means of bolts.

- Next the roof components must be installed with the use of a ladder.

- Once the assembly process has been completed, the bolts and screws should be screwed into place and the connections between the wall components, walls and floors must be covered with adhesive tape to protect them from leakage (see Fig. 7.11).

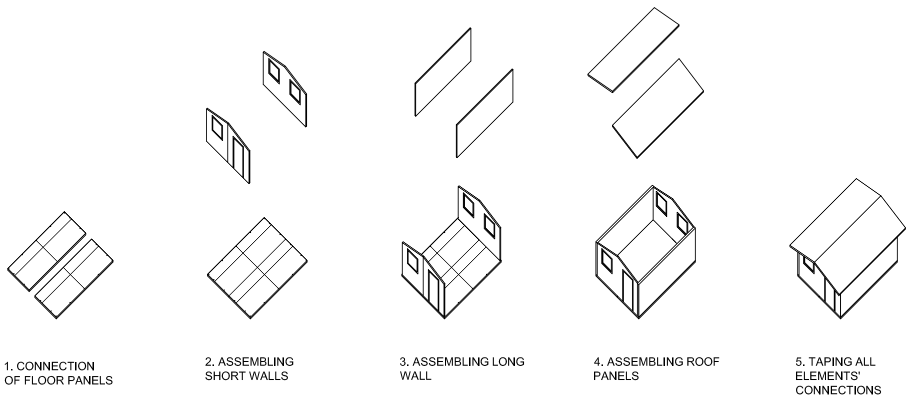

FIGURE 7.10 Assembling scheme of TECH 01

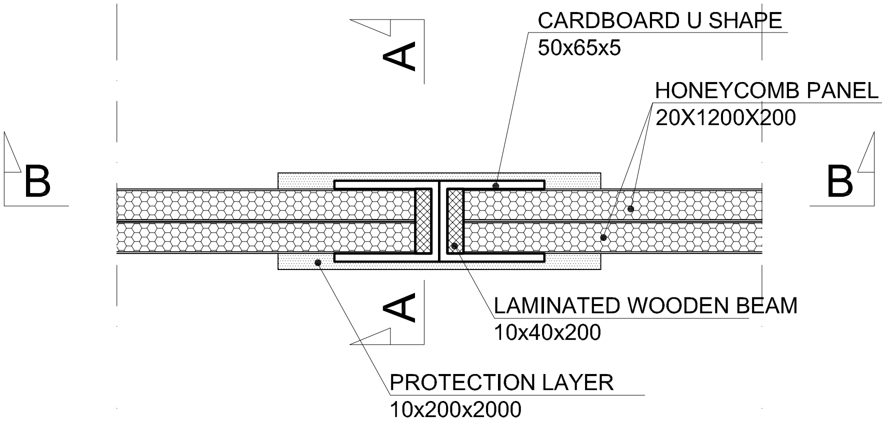

FIGURE 7.11 TECH 01 detail of the wall panels connection

TECH 01 is a prefabricated house whose components are prepared off site. Elements such as honeycomb panels, U-shaped cardboard profiles, plywood, OSB boards, windows, doors and beams will all arrive at the factory in the desired dimensions. The elements are then impregnated – i.e., covered with a protective layer – and painted if desired. Later they are dried at the factory's carpentry shop and drying plant. Once the drying process has been completed, the elements are delivered to the main hall of the factory, where they are assembled in three separate assembly lines: a roof panel line, a floor line and a wall line.

Once the components have been assembled and undergone quality and dimension control, they are packaged and several packs are transported together in a twenty- or forty-foot shipping container. Each TECH 01 flatpack (containing a 17.4m² unit) will measure 580 by 230 by 75cm.

After arriving at the desired destination, the components are unloaded from the container and prepared for the erection of the house.

§ 7.3.4 Evaluation

TECH 01 is a project of temporary and emergency shelter which was designed to replace the typical UNHRC family tents. The possible rearrangement of the shelter layout gives broader opportunities to use the structure not only as a housing unit.

The shelter consist of several components which can be stored and transported by means of shipping containers. The wall and roof panels are composed of U-shapes frame filled with honeycomb panels. The timber joints are integrated into the panels. Such a solution allow the builders for acceleration of construction works. The prototype of the wall panel was built in order to check the feasibility. The connection between the floor and wall panels need to be further elaborated. As the project was finalized in the concept phase the impregnation was not taken into account. The production, transportation and building processes were thought through. In case of serial production the concurrent manufacturing, where several components are produced in the same time can be adapted. The project was a proposition for the northern Iraq, where many refugees stay in the camps and the housing conditions are poor.

§ 7.4 TECH 02

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Tutors: Jerzy Latka, dr Marcel Bilow
Year: 2015
Location: Iraq
Area: 13m^2 (size M)
Lifespan: Temporary (estimated lifespan five years)
Type: Emergency / temporary shelter

After the evaluation of the TECH 01 project and analysis of the technical solution the design objectives for the next version of Transportable Emergency Cardboard House were set. The TECH 02 was designed and build by group of students supervised by author of this thesis and dr Marcel Bilow. The various aspects of the project were elaborated in sub-groups. The project was realized during the Bucky Lab course at

Faculty of Architecture TU Delft in summer semester 2014/2015. At the end of the course, the prototype in 1:1 scale was built.

§ 7.4.1 Design objectives

On the basis of the previous project of TECH 01 the structural system was chosen as a beam-and-column rod structure. The frame structure was decided to be made pout of U- or L-shapes, and the wall and roof panels out of corrugated cardboard or cardboard honeycomb panels.

The size of the shelter should not exceed 17.5 m^2 and it should be composed of building elements and components which can be pre-fabricated and deliver to the building site. The size of the shelter should allow the builders to be constructed without using any special equipment.

The destination are of the project was the north Iraq and Kurdistan.

§ 7.4.2 Project concept

TECH 02 is a single-space unit with a usable area of 12.96m^2. It consists of prefabricated components that are shipped to the site and assembled by the future inhabitants of the unit. Since the structures are to be erected by non-professional construction workers, their design must be basic and readily understood by regular people. Depending on the inhabitants' needs, the wall panels can be equipped with a fixed door or window. The units can be clustered so as to create a row of houses or bigger buildings, such as school buildings. The initial design assumed a nested arrangement, in which four units were put together, with a common space in between. A common sanitary, heating and cooking unit could be installed in that shared space.

Three different layouts were proposed for TECH 02, each linking private houses with semi-public and public areas in a different manner. The layouts formed easy-to-build patterns that organised:

- Roads and public spaces
- Shared community spaces, semi-private spaces and entrances

– Optimal orientation vis-à-vis the run for passive energy gains

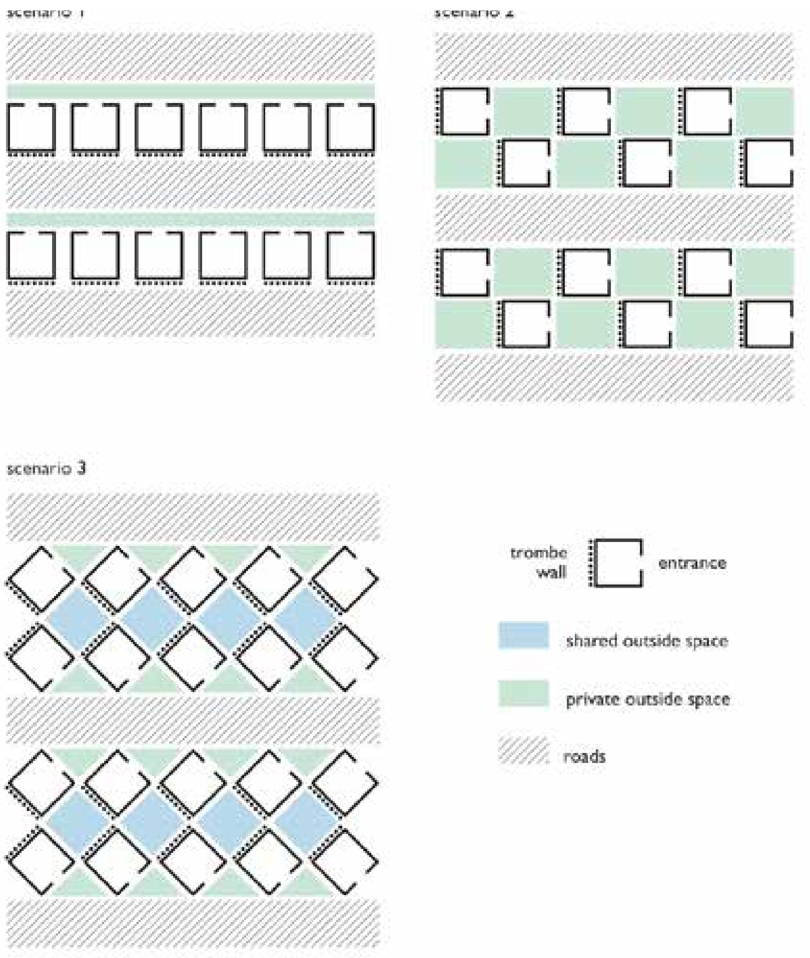

FIGURE 7.12 Spatial arrangement of TECH 02

The structural system used in TECH 02 is a rod system. Beams and columns are the most important load-bearing elements. The building consists of prefabricated components of modest dimensions, so that the whole structure can be erected by manpower, without any need for heavy equipment. Since the wall panels all have the same dimensions, the layout of the house can be rearranged. Elements such as windows, doors and Trombe walls can be installed in accordance with the directions of the sun.

Since the house is made of rigid materials and has solid floor panels, walls and roof elements, the inhabitants will experience a sense of security, privacy and homeliness. The wall panels are made of cardboard elements, so their outer layer can be printed to allow the inhabitants some form of customisation. The printable surface of the walls can also be used for advertising for the companies supporting the project.

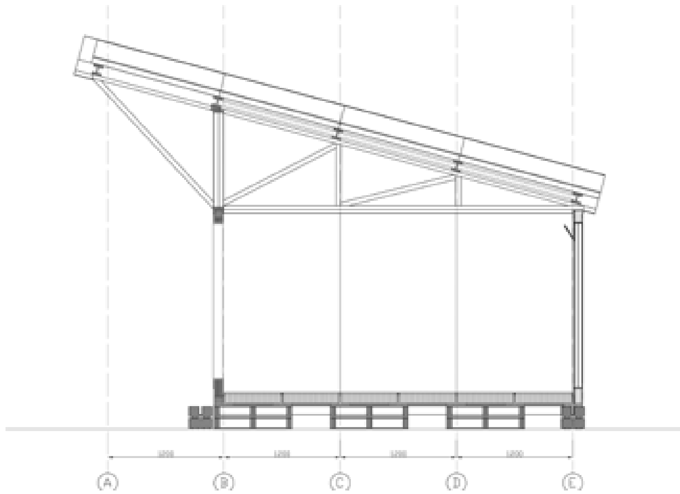

FIGURE 7.13 TECH 02 floor section

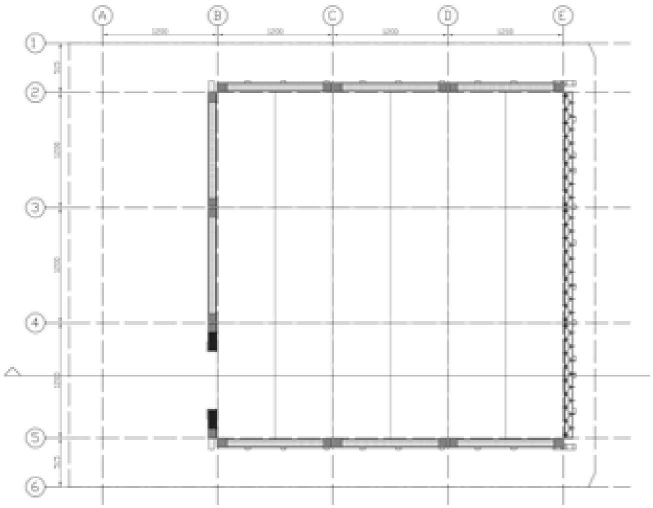

FIGURE 7.14 TECH 02 floor plan

As the proposed location for the camp was northern Iraq, the climate was obviously a major factor that had to be taken into account in the design of the unit. Research indicated that Iraq has three types of climatic conditions: arid/desert, semi-arid/steppe and Mediterranean. Only the latter two types of climate can be found in northern Iraq. A Mediterranean climate is characterised by warm-to-hot and dry summers and mild-to-cool wet winters. A semi-arid/steppe climate is characterised by hot or even extremely hot summers and mild or warm winters. Two cities in the north of Iraq were taken into account as representative locations for the climate assumptions: Mosul and Sulaymaniyah. Mosul can be extremely hot during the summer, and temperatures can rise to 48 °C and drop to -11°C during the winter. Therefore, this city was chosen as a potential location. Other circumstances to be considered were rain and snow, which appear during the year. The sun path in Iraq was examined in order to help design the roof. The angle of the sun is 28° on the 21th of December, and 73° on the 21st of June.

§ 7.4.3 Technical and material solutions

Foundations and floor.

Several types of foundations were considered. Deep foundations such as piles, piers, caissons were found to be undesirable because they require intensive preparation, e.g. deep excavations. Shallow foundations, sub-divided into spread footing/open trench foundation, pad foundation, strip foundation, grillage foundation, raft foundation and inverted arch foundation, seemed to be more suitable for the construction of emergency houses.

Northern Iraq has mountainous terrain: the Zagros mountains. Therefore, the foundations used for TECH 02 had to compensate for unlevelled terrain. The soil in the area is rather rocky. Because of the brown soil and rough mountain scenery in this region, digging the land is hard.

The following objectives were assumed for the foundation and the floor:

- Due to the enormous temperature differences (-11 °C in winter to 48°C in summer), the floor should be well insulated
- Airflow under the floor is a beneficial solution for extremely hot seasons
- In the winter airflow under the house is not desirable due to the fact that cold air will negatively affect the insulation of the house
- The structure must be water- and snow-resistant. Since cardboard is used as a construction material, this is an extremely important aspect. The floor should be at least 20cm off the ground, to prevent the risk of flooding
- A watertight layer should be installed between the floor and the foundation
- Nothing should be left in the ground once the unit has been demolished
- Rocky and uneven terrain requires levelling of the ground
- The floor should have high thermal insulation values
- Floor panels must be watertight on both sides: from the outside because of rain and flooding, from the inside because of spilt water
- All components should be able to be carried with ease by two persons
- The structure should be kept in the place despite of wind loads by means of foundations and other possible solutions:
  - Weights on the ground (sandbags, cardboard boxes filled with stones)
  - Anchored to the ground by canvas, cables or wires
  - In-soil foundations: poured concrete, drilled or hammered piles into the ground
- The foundations and floor should form a well-functioning system with the walls.

The foundation blocks were made out of EURO pallets used for transport. The size of each foundation block was 200x800mm, which means that they were cut from standard-size EURO pallets measuring 800x1,200mm. The pallets were put on the ground, which had been prepared and levelled (where necessary) beforehand, and stacked in pairs on top of each other (see Fig. 2.15). The space between the planks of the foundation blocks was used for UFAD (under-floor air distribution) and for bags filled with sand or stones, which added some weight to the structure.

The floor consists of two parts: beams and floor panels. The beams were composed of two L-shape profiles of full cardboard, measuring 100x100mm, with walls 10mm thick (see Fig. 7.16). These were glued together in the form of a T-shaped beam or cross-shape beam. The cross-shape beams were placed at the edges of the foundation and were used to connect the floor structure to the walls. The T-shaped beams were placed downwards when placed on the foundation blocks, so the beams were able to fit into the slot between the planks of the foundation block. On top of this structure, T-shaped beams were placed upwards in the opposite direction. All the beams were connected to the foundation blocks by means of screws. The upturned T-shapes of the second layer of the floor beams created a grid which was filled with floor panels.

The floor panels were composed of two OSB layers measuring 1,200x600x18mm on the top and the bottom and five layers of honeycomb panels measuring 1,200x580x20mm. The elements were glued together. The two OSB layers helped to achieve a waterproof layer and reinforced the panels.

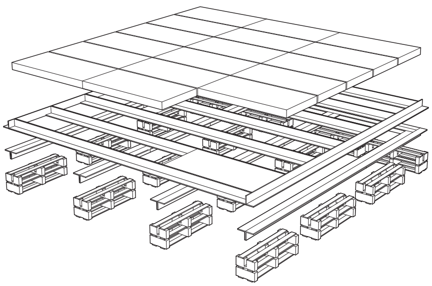

FIGURE 7.15 Exploded axonometric view of foundation and floor structure

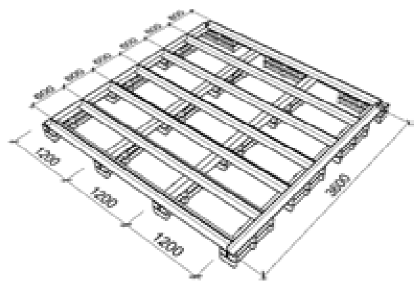

FIGURE 7.16 Axonometric view of foundation and floor structure

Walls

In the early stages of the process the initial ideas of the wall structures were considered and combined into a matrix in which all the pros and cons of the different properties were assessed.

Since the stability of the shelter depended on its wall system, certain design objectives for the wall structure had to be assumed:

- Due to the need for thermal insulation and the fact that the walls would be load-bearing, two types of the wall should be considered:
  - Filled load-bearing wall (or cavity wall), filled with local materials
  - Lightweight sandwich panel wall with secondary load-bearing frame structure
- Transportation issues refer to the size and weight of the building components. To ensure hassle-free transportation, all the elements should be able to fit into a twenty-foot shipping container and onto a standard EURO pallet. These requirements resulted in a maximum cargo height of 2.20m and a maximum cargo width of 1.20m.
- For local people to be able to assemble the housing units without any problems and with little manpower, the units had to be lightweight and consist of very basic components. The maximum weight lifted by one was estimated to be 30 kg. Therefore, the maximum weight of one single wall component should not exceed 60 kg, to allow it to be lifted by two persons.
- The structure should be designed in such a way as to allow non-professional construction workers to erect it quickly and easily. By implementing smart design solutions, the designers could guarantee that no heavy equipment would be needed to erect the structures.
- The relationship between inside and outside, i.e., the positioning of the door and windows, should be flexible and able to be changed depending on the layout of the site and the cardinal directions.
- The wall panels should have good thermal insulation values in order to provide a comfortable living space in extreme conditions, with temperatures ranging from -11°C to 48°C.
- A passive-energy system like a Trombe wall should be affixed to the wall panels that are exposed to sunlight coming from the south-east or south-west.
- The wall structure should be properly impregnated against water, fire, moulds and insects. At the very least, the frame structure should be carefully impregnated against water, and the wall panels should be easy to replace in case they get damaged by weather conditions.

The walls were divided into two elements: a load-bearing frame structure and wall panels.

The frame was composed out of L-shapes measuring 100x100x10mm and 2,000mm long which served as columns. There were two different types of columns: corner and middle ones (see Figs. 7.17 and 7.18). The four corner columns consisted of three L-shapes laminated together to form a cross-in-section profile. The middle columns were composed of two L-shapes glued together to form a T-shaped column. There were eight middle columns, i.e., two for each wall.

FIGURE 7.17 Corner column

FIGURE 7.18 Middle column

Wall panels

As far as construction was concerned, there were two different types of wall panels: regular wall panels and special Trombe wall panels. All the panels measured 120x200cm, regardless of their type. This allowed the creation of a modular wall system and allowed the wall panels to be installed in different positions, depending on the climatic conditions and cardinal directions.

The regular wall panels measured 120 by 200cm and were between 85.6 and 92mm thick. The regular wall panels were composed of several corrugated boards and honeycomb panels laminated together. A wooden block measuring 9 by 9cm was attached to each corner of the panel (see Fig. 7.19). Then the whole panel was covered on both sides with additional layers of corrugated board. The wooden blocks were used for fixing the panels to the load-bearing frame construction built out of T- and X-shaped columns. The edges of the panels were sealed by strong duct tape. The panels were 9cm thick. As a result, the wall panels beautifully fitted into the frame structure.

Three different options for the composition of the regular wall panels were designed and prepared in order to test their properties and mechanical behaviour in a final prototype structure. The options ranged from a combination of honeycomb and corrugated board to completely corrugated plates (see Fig.7.20).

Option one consisted of three 20mm thick honeycomb panels alternating with two five-layered corrugated boards that were 6.4mm thick. Additional corrugated plates were attached on both sides to keep the wooden blocks in position and to protect the honeycomb panels. This panel was 85.6mm thick.

Option two consisted of two 30mm thick honeycomb plates alternating with three plates of five-layered corrugated boards with a thickness of 6.4mm. Additional corrugated boards were glued to the outer surface of the panels in order to hide the wooden blocks and keep them in position. This panel was 92mm thick.

Option three consisted entirely of corrugated boards. As corrugated board has the best mechanical properties in the longitudinal direction of the corrugation, the boards were laminated in two perpendicular directions so as to make them stronger and more rigid and so better able to withstand vertical and lateral forces. Additional corrugated board plates were attached to cover the wooden blocks. The thickness of panel no. 3 was 89.6mm. It was composed of fourteen five-layered corrugated boards, each 6.4mm thick.

Out of the three aforementioned options, option no. 1 was the best solution, because it was lightweight and had good thermal insulation properties. Option no. 3 was far too heavy and option no. 2 had lower thermal insulation values due to the smaller number of air cells in the individual boards.

FIGURE 7.19 Wall panel

FIGURE 7.20 Wall panels, a) option one, b) option two, c) option three

Furthermore, special panels incorporating doorways and window frames were prepared. These panels were composed of layers of honeycomb and corrugated board, combined in the same manner as the regular wall panels. The doorways and window openings were covered with L-shapes in order to get a protected frame ready for the installation of a door or window. The window was incorporated into the panel during the prefabrication process. The doors are to be installed on the site.

Cardboard in its solid form has high thermal insulation properties. According to CES EduPack's website, soft cardboard has a thermal conductivity of 0.12 W/mK, which is almost three times better than common wood materials like plywood or OSB, whose thermal conductivity is 0.35 W/mK. However, these properties are changed significantly when cardboard is used in the form of corrugated boards and honeycomb panels, whose small cells contain trapped air. Air has a conductivity value as low as 0.02 W/Km, so if air is trapped inside the cardboard elements and the cells are small enough that the air is not moving, the thermal insulation value of such material increases. A wall element consisting of two layers of honeycomb alternating with corrugated plates was modelled in the TRISCO software package. A simulation was carried out at an established outdoor temperature of -10°C and an internal heat load of five persons, as each unit is designed for one family consisting of five members. The results showed that this situation would be enough to maintain an indoor temperature of 18°C.

In order to achieve passive energy gains, one of the walls was designed to be a cavity wall making up a Trombe wall system.

Trombe wall systems use thermal mass and cavities between the mass and the transparent material to provide passive ventilation, heating and cooling. This system was proposed in order to temper Iraq's frequently very high temperatures (see Fig. 7.21).

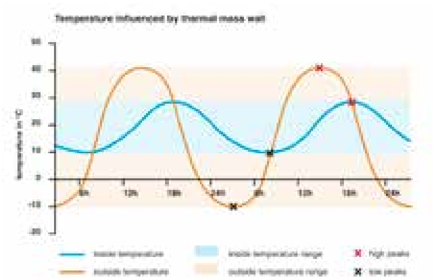

FIGURE 7.21 Temperature influenced by thermal mass wall

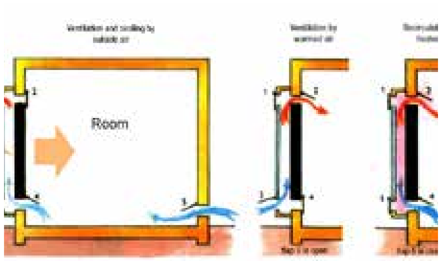

FIGURE 7.22 Trobme's wall principle diagram, source [8]

The principle behind Trombe walls is centred around the thermal mass and cavities between the mass and the transparent material which is applied to the outside of the wall. Thermal mass, usually painted dark, soaks up heat during the day. In the evening it will radiate the heat it has collected during the day into the room. In addition, Trombe walls can be used for cooling and ventilation purposes. Trombe walls can be used in three different situations, which will be outlined below (see Fig. 7.22).

In the first situation, heated thermal mass is used to create underpressure between the thermal mass and the transparent layers. This will cause the air to be sucked out and leave through a gap at the top of the wall. Fresher and cooler air is sucked in from the gap under the door. In such cases, where the inside temperature is higher than the outside temperature, the system works as a cooling system.

In the second situation, air that enters the cavity from outside through a gap at the bottom of a wall is heated up by the thermal mass in the Trombe wall before getting into the room. This solution can be used when the outside temperature is lower than the inside temperature and the room needs to be heated.

In the third situation, inside air is circulated back into the room through the Trombe wall. The air does not leave the unit; it circulates inside the room and the loss of heat is prevented.

The best orientation for a Trombe wall is south, south-west or possibly south-east. As can be seen in the layout of the TECH 02 units, the Trombe wall (marked by dots) always faces the desired direction.

The basic idea behind the Trombe wall was incorporated into the cardboard structure. The wall should contain a filling material and should transfer the forces to the foundations. Air should be guided to the cavity, which has to be covered by a transparent material in order to allow the thermal mass to be heated. The system should enable one to control the air flow between the interior and exterior.

TECH 02's Trombe wall panels measure 1,200x2,000x 110mm. Each panel consists of a bottom and top chamber with openings to both the interior and the exterior of the house, and a part in the middle with air cavities and filling cavities (see Fig. 7.23). The bottom and top chambers are composed of L-shape profiles laminated together in the form of Z-shape profiles. Wooden blocks measuring 90x90mm are attached at both ends of the rows of Z-shape profiles in order to mount the Trombe wall panel in the same manner as the other panels. The air cavity and filling cavity are made of laminated L-shapes in the form of a zigzag pattern that divides the wall panel into two parts. One side can be filled; the other is left open to serve as an air duct. Eight triangular cavities have a filling volume of 0.034m^3. The triangular division on the outside is painted black and closed off with Plexiglass. Inside the wall, the filling cavity is covered with plywood. Three types of fillers were considered for the project: sand, which weighs 1,400 kg/m^3 (0.034m^3 results in 48 kg), pebbles weighing 1,000 kg/m^3 (0.034m^3 results in 34 kg) and sheep's wool, the lightest material, weighing 22kg/m^3 (0.034m^3 results in 0.8 kg). All the above materials were considered as local and dry materials that might be used as a filler. While sheep's wool has very high thermal insulation properties, it also has low mass. For this reason, it is not advisable to use sheep's wool as a thermal mass filler.

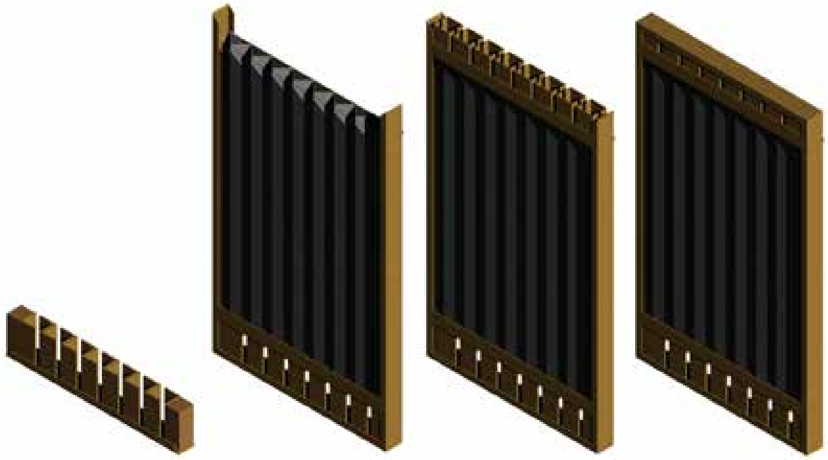

FIGURE 7.23 Trobme's wall panel

Roof.

Research into different types of roofs was conducted at the beginning. Nine different roof structures were considered: dome, chapel roof, textile roof, double-curved roof, tropical roof, flat roof, pent roof, folding roof and cable roof.

At the next stage, design objectives were carried out:

- The roof is mainly made of cardboard
- Roof components must fit into a shipping container
- The roof components must be small enough to allow people to place the roof over the wall structure using just manpower and regular tools (i.e., no heavy equipment).
- The design of the structure must be easy enough to allow non-professional construction workers to erect the structure
- The roof must come with thermal insulation material
- The form of the roof must allow for passive cooling, which means a tropical roof solution is desirable
- The roof must have at least a 15-percent slope in order to allow snow and rain to slide off. A sloping roof may provide the house with additional lighting
- The eaves must overhang, thus protecting the walls from rain and creating a semi-dry space for outdoor activities
- The roof structure must be rainproof

- The roof structure must be demountable in the event that one of its components gets damaged and must be replaced.

It was decided that the unit would have a single pitched tropical roof. In a tropical roof the layer of air between the top of the roof and the interior of the shelter is heated. The heated air inside the roof will start to flow upwards and so ventilate away heat which otherwise would have entered the shelter. This solution is desirable during the day, when the heat of the sun can raise the temperature in the shelter. At night, the air between the various roof layers should be preserved in order to provide additional thermal insulation. For this reason the tropical roof should be closed at the end of the day so as to create an air pocket (see Fig. 7.24).

In addition to using a tropical roof, the group considered the Venturi effect. This effect is caused by the accelerating velocity of the air stuck inside the roof. Decreasing the cross-section of the air flow will result in accelerated flow, which in turn results in additional ventilation, due to pressure differences.

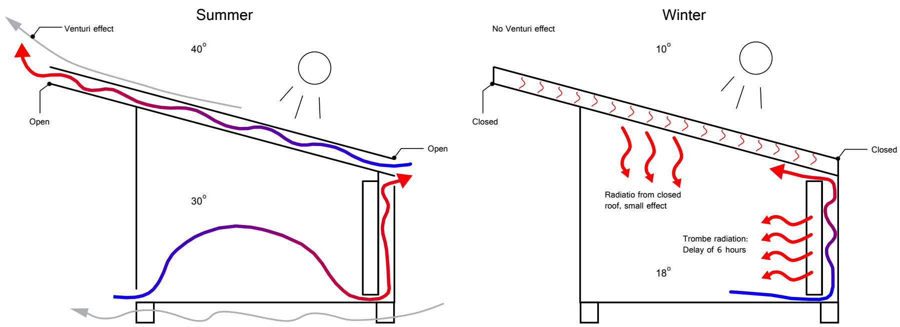

FIGURE 7.24 Tropical roof, venturi efect and Trombe's wall scheme

In order to create a tropical roof with a Venturi effect, the team had to come up with a special roof structure. This roof consists of four elements:

- A truss, which provides the slope and cantilever that will create a semi-dry and semi-covered outdoor space where daily activities can be carried out. The truss structure is composed of cardboard U-profiles connected to wooden planks. As a result, it is a lightweight and stable structure. Two trusses are attached to the tops of the side walls.

The trusses are covered on the outside with Plexiglass, which will allow natural light to enter the house. Between the trusses, at the front of the house, there is a window frame over the entrance. This window frame stabilises the trusses in the other direction.

- Five H-beams composed of laminated U-profiles and 9mm wooden laths are attached to the tops of the trusses. The H-profile beams carry the actual roof plates and honeycomb panels between the beams for additional thermal insulation. The span of the beams is 4.6m. They cover

- The roof plates at the tops of the beams are made of corrugated board folded into triangular tubes. The tubes create channels which is to say they allow the air to flow inside the roof structure. The triangular tubes can be used as a thermal insulation method during the cold season by closing the flaps at the ends of the channels. To create the channels, corrugated plates are hooked into each other and are folded in the form of triangular tubes. The direction of the corrugation determines the strength properties of the roof plates. If the corrugation travels sideways, the triangles will be more dimensionally stable. If the corrugation travels lengthwise, the cardboard will be stronger, and it will bend rather than tear. The results of the material tests described in Chapter 2 showed that the orientation of the triangles makes a significant difference. Triangles pointing up will bend, whereas triangles pointing down will break. The bottom plate with the triangles pointing up is folded along the corrugation line in order to assimilate the tension. The upper layer of the roof plates with triangles pointing down is folded perpendicularly to the corrugation to assimilate the tension and make the plate stable.

- The final layer of the roof is a protective layer made of corrugated cardboard covered with waterproof and fire-retardant foil. This protective layer is wrapped around the beams and is connected with the truss. An L-shaped beam is installed under the roof beams, where it serves as a sill.

The trusses are connected to the walls with U-profiles attached to the bottom of the truss and to the tops of the walls. The U-profiles are screwed to the wooden connector of the truss and the wooden blocks of the wall panels.

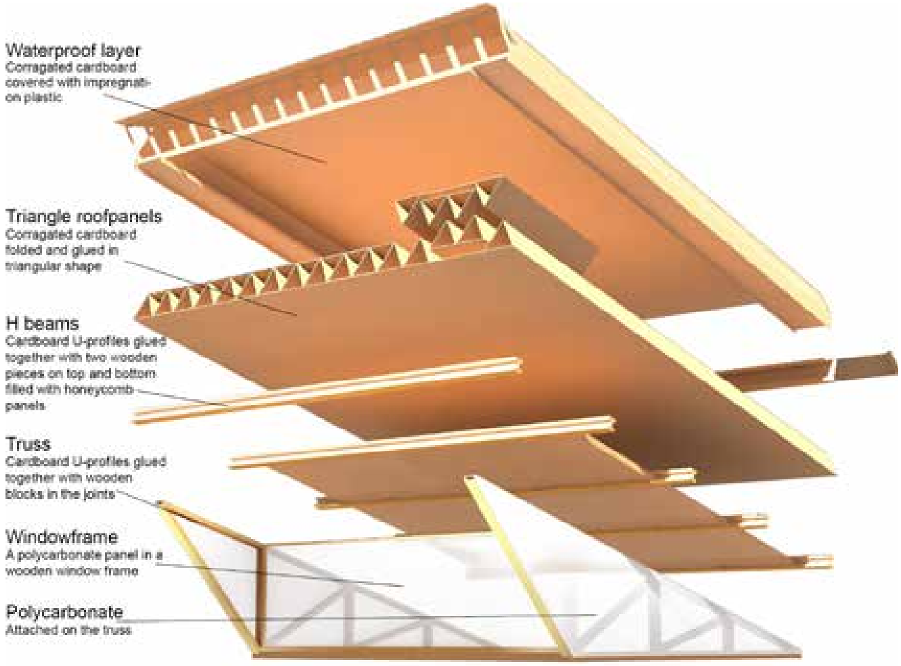

FIGURE 7.25 Roof structure

§ 7.4.4 Prototyping

The building process started with foundations (see Fig. 2.26). Next the corner X-shaped columns were screwed to the wooden foundation through the wooden corner blocks. The first wall panel was connected with an X-column by means of screws. Then a T-shaped column was attached to the panel and the foundation (see Fig. 7.27). The next wall elements were mounted in the same manner until one entire wall was standing upright. Three wall panels and two intermediate T-shape columns created one wall slab. Once all twelve panels had been attached to the foundation, the base for the roof (i.e., U-shaped beams with a 110mm outer width) was placed on top of the walls and screwed to the wooden corner blocks in the wall panels (see Fig. 2.29). Since the wall panels all have the same size, i.e., 1,200x2,000mm, they could be used interchangeably, thus different configurations of the regular and special panels was allowed, depending on the situation on the site (see Fig. 2.28).

FIGURE 7.26 Foundation and floor

FIGURE 7.27 Cardboard T-beam

FIGURE 7.28 Wall panel

FIGURE 7.29 Construction of the roof

The building process of the wall started with the corner X-shaped columns. The columns were screwed to the wooden foundation through the wooden corner blocks. Next the first wall panel was connected with an X-column by means of screws. Then a T-shaped column was attached to the panel and the foundation. The next wall elements were mounted in the same manner until one entire wall was standing upright. Three wall panels and two intermediate T-shape columns created one wall slab. Once all twelve panels had been attached to the foundation, the base for the roof (i.e., U-shaped beams with a 110mm outer width) was placed on top of the walls and screwed to the wooden corner blocks in the wall panels. Since the wall panels all have the same size, i.e., 1,200x2,000mm, they could be used interchangeably, thus different configurations of the regular and special panels was allowed, depending on the situation on the site.

Impregnation

There are many ways of applying a waterproof coating to cardboard. Cardboard elements can be laminated with plastic film, sprayed with an exterior plastic coating, painted or dipped in lacquer, impregnated with wax coating or being impregnated with method called cascading, which saturates the cardboard with a hot wax substance. It is also possible to impregnate cardboard with biodegradable coating made from the pulp of sugar cane.

The research of different application methods was conducted. Because of the financial and time shortage only the exterior application of the coating was taken into account. Several different products available on the market were tested. The impregnation tests were also conducted during the realization of the Wroclaw Exhibition Pavilion, which was composed of wooden arcs and paper tubes. The paper tubes were preliminarily impregnated with several different products and then tested.

For TECH02 impregnation the products available on Dutch market were tested. After the research and choice of products, impregnation tests were conducted.

- Gummil Premium Liquid Rubber – this water based product can be applied to the surface in form of paste and after drying becomes a rubber. Gummil should be applied with a roller, brush or airless spraying. The big advantage of the product is its total air- and waterproof quality and high flexibility, therefore applied to surface it is not sensitive to movements of substrate or rapid changes of temperature.

- Nr. 1 Wood Protector – is used for waterproofing, water- and dirt-repellent of wood. This product can be used only with untreated wood and can be applied with brush, roller and low pressure spray. It ensures optimal protection against moss, agleam fungi and weather conditions as well as UV-protection against decolourisation.

- Hempel Dura Satin Varnish Lacquer – a quick drying, silk gloss urethane alkyd varnish. It has a good resistance to seawater, sunlight and adverse weather conditions. Product can be applied to new and previously varnished wood for interior and exterior.

- Ruwa Jacht Lacquer is a strong transparent yacht varnish which is suitable for all woodwork and topcoat for furniture.

COMPARISON	Gummil Premium Liquid Rubber	Nr. 1 Wood Protector	Hempel Dura Satin Varnish Lacquer	Satin Ruwa Yacht Lacquer
Water-resistance	++	+	++	+++
Price	+	-	-	--
Quantity of material	++	+	-	-
Fire-resistance	+	-	+	+
Insects- or pets-resistance	+	+	++	++
Mould-resistance	+	++	++	++

TABLE 7.2 Comparison of different impregnation products

For the impregnation test some specimens were prepared. The specimens were tested by spraying or dipping them in water for a period of ten minutes. The previous research on impregnation of Exhibition Pavilion of Wroclaw University of Technology brought basic knowledge of the impregnated material behaviour, thus after even short time it was possible to assess the quality of impregnation (see Tab. 7.2).

Test 01.
T-profile was impregnated with Gummil Premium Liquid Rubber and Nr 1 wood protector. The rubber was painted on the profiles and the wood protector was sprayed. The best results were achieved by specimen 01 which was completely painted by Gummil. Specimens 02 and 03 were sprayed with Nr. 1 wood protector and the cut parts were painted with Gummil. Difference between specimen 02 and 03 was that in specimen 03 also the gap between laminated L-profiles was protected with Gummil. Results for specimens 02 and 03 were not satisfactory (see Fig. 7.30).

Test 02.
Six specimens of U-profiles were painted with two different lacquers (Hempel and Ruwa). For each lacquer two specimens were painted and the ends were impregnated with Gummil. One specimen of each lacquer was dipped. The tests showed that Hempel Dura Satin Varnish Lacquer brought the best results. However this product is very expensive (see Figs. 7.31 - 7.33).

FIGURE 7.30 Impregnation test 01

FIGURE 7.31 Test 02 - impregnated elements

FIGURE 7.32 Test 02 - deeping specimans in water

FIGURE 7.33 Test 02 - results

The foundations consist of parts of EURO pallets and T-shaped beams made of cardboard. As the wood used in the project is not a subject of this dissertation, only the impregnation of the cardboard elements is discussed here. EURO pallets are built out of impregnated timber and can be provided with an additional layer of impregnation by using waterproof paints popular on the market.

The cut ends are the most vulnerable parts of the T-shaped beams. In fact, this is the most fragile part of the entire structure, since water and moisture can get into the material here, dissolve the water-based saccharide glue used for the production of the profile and destroy the bonds between the cellulose fibres in the material through hydrolytic degradation. Therefore, special treatment is needed for these parts of the structure. The edges of the T-shaped beams were impregnated with Gummil Premium Liquid Rubber, while Ruwa Jacht Lacquer was painted on the gaps between the two L-profiles. Due to time and budget constraints, the floor beams covered by the floor panels were left untreated.

The wall structure consists of two different types of elements: a load-bearing frame structure (columns composed of cardboard L-shape elements laminated into T- and X-shaped columns) and wall panels. As water poses a severe threat to structural elements made of cardboard and paper-based products, it is absolutely crucial that these structural elements be impregnated very carefully. A few different impregnation techniques were applied, depending on the element to be impregnated.

Following lamination, L-shaped and X-shaped columns were impregnated with Ruwa Jacht Lacquer. The cut edges of the profiles were additionally impregnated with Gummil.

The wall panels on the exterior side were covered with self-adhesive plastic foil. The foil demonstrated the following properties: water-resistance, smouldering when subjected to fire and transparency. Since the foil was only 60cm wide, several overlapping layers had to be applied. To prevent leakage, the edges of the panels were additionally covered with duct tape. The foil was applied only on the exterior side in order to let the panels breathe, so that if any moisture were to get into the panel, it would not destroy the material but rather evaporate.

In addition, duct tape was used to cover the gaps between the columns and the wall panels.

The truss elements were impregnated with Ruwa Jacht Lacquer after being glued to each other and glued connected with the wooden slats. The roof plates, composed of triangular corrugated plates, were not impregnated at all on this occasion. However, if the shelter were to be produced for a one-to-three-year lifespan, impregnation of all the materials would be required. The covering layer, which consisted of corrugated plates, was wrapped in plastic self-adhesive foil. Furthermore, the connections between the foil layers and the sides of the panel were covered with duct tape.

The TECH 02 prototype was exhibited at the campus of the Faculty of Architecture and Built Environment TU Delft for about a week. Afterwards, the structure was dismantled and the building elements were send to be recycled (see Figs. 7.34 - 7.39).

FIGURE 7.34 TECH 02 prototype at Faculty of Architecture TU Delft, 2015

FIGURE 7.35 View on the Trombe's wall panel

FIGURE 7.36 Interior of the TECH 02

FIGURE 7.37 Structural elements of TECH 02

FIGURE 7.38 TECH 02, window frame

FIGURE 7.39 Dismantled and ready to be recycled TECH 02

§ 7.4.5 Evaluation

The project of TECH 02 was designed to withstand extreme boundary conditions. In other words, it was a challenge to use all the possible passive energy gains of the proposed design to heat up or cool down the shelter. The chosen site was in the north of Iraq, near the city of Mosul, where temperatures can drop to -11°C in winter and rise all the way to 48°C in summer. The region sees both rain and snow. The soil in that mountainous area is rocky, which makes it hard to dig in it.

TECH 02 was exposed to external weather conditions for six days. Unfortunately, it had to be disassembled after this period.

The foundation elements were made out of Euro pallets, which was low-cost solution. However there were too many elements that had a contact with ground. This could cause the problems in the situation where the ground is not perfectly levelled. It is suggested to develop another foundation system, where only several elements have a direct contact with the ground. The T-shape beams on the floor worked well, butt on the other hand in case of water spill inside of the shelter, they might get damaged (see Fig. 7.40). Therefore for floor elements the timber is favoured material. The sandwich floor panels were stable and strong enough to carry the weight of several persons.

FIGURE 7.40 Floor component

FIGURE 7.41 T-shaped pillar

The structural system worked well, the connection between T-shape beams and the wall panels gave sufficient stability, hence no extra stiffen was needed such as diagonal bracing (see Fig. 7.41).

At the corners of the structure, the X-shaped pillars were exposed to the natural condition. This should be revised and another solution, where all the structural elements are hidden from external condition should be developed.

The roof structure should be reconsidered and some alternative solutions should be proposed. TECH 01, the previous version of TECH 02, included a double-pitch roof composed of two plates connected to each other at the ridge. This solution is easier in terms of transportation, erection and usage, but will not provide a tropical roof, nor the Venturi effect.


FIGURE 7.42 Roof structure made out of U-shapes


FIGURE 7.43 Inlets of the tropical roof

The roof is the most significant part of the structure of the house. It makes the interior comfortable and provides shelter from the elements. The roof is the most complicated part of the house, and is also the part of the structure that is most exposed to the elements. Therefore, special attention should be paid to this part of the house.

Some other roof structures that may have potential are outlined below. Further research should focus on the proposed solutions with regard to the material used for the load-bearing structure, impregnation, transportation issues and ease of erection. The proposed type of roof should be treated as a guideline for further research and prototyping.

Different roof types have their own characteristics which can be applied to structures designed for different regions, depending on the local climate.

Flat roofs with a slope between two and ten degrees are predominantly used in hot and dry areas with very little rain. Such roofs are not appropriate for areas with strong winds and hurricanes, as the wind will simply pull off the roof. The material proposed for decking is bituminous roofing felt, especially self-adhesive and modified bitumen types of felt (SBS and APP type) or liquid finishes.

Single pitched, gabled and hipped types of roofs can be used in warm and humid regions with significant precipitation. If the roof slope exceeds thirty degrees, the roof is appropriate for hurricane areas, since flatter roofs (ten to thirty degrees) create suction forces. Wide overhangs are appropriate for areas with a lot of rain. They cover and protect walls against being soaked by rain. Hipped roofs protect all walls, while gabled roofs only protect the side walls, but they are more difficult in construction. A roofing felt, bitumen, liquid finishes or various plant materials such as thatch or matting can be used as a finishing layer.

Shell structures and bow-string roofs are suitable for earthquake-prone areas. However, they are expensive and hard to produce. Some shells can be prefabricated (e.g. polyurethane igloos) but they seem inappropriate for dwelling purposes.

Other types of roofs are tensile roofs, folded plate roofs and air-supported roofs. Since TECH was designed as a cardboard structure, inflated and tensile roofs do not meet the brief. However, future researchers may wish to focus on a combination of cardboard and textile tensile structures. Folded plate roofs may be a good solution if they are made of cardboard elements, but research on such a solution was not within the scope of this dissertation.

Roof structures and shapes should not only be dictated by local climatic conditions. Like the rest of a structure, the shape of the roof is determined by socio-cultural aspects like religion, family and clan structure, building traditions, attitudes towards the environment, mobility, etc. As TECH is a proposed emergency shelter aimed at inhabitants of different cultural and geographical regions of the world, such aspects should be possible to be changed in specific cases.

A few other examples of possible roof structures involving cardboard elements are listed below. Further research will be required to develop such structures. At this stage of the research they represent different possibilities and forms:

- Double pitched roof
- Double pitched roof with truss
- Flat roof
- Vault roof
- Roof with a reflective surface

§ 7.5 TECH 03

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Year: 2016
Location: Wroclaw, Poland
Area: various (size M)
Lifespan: Temporary (5 years)
Type: Emergency shelter/ Housing

TECH 03 is the final product, based on two previous attempts and research. The prototype of TECH 03 was known as the House of Cards. The House of Cards was awarded the first prize in the FutuWro competition. [9] The project was realised as part of the City of the Future/ Laboratory Wroclaw programme, undertaken when Wroclaw was a European Capital of Culture in 2016.

§ 7.5.1 Design objectives

The House of Cards was a type of temporary housing designed for asylum seekers, refugees who have fled their homes and homeless people living in Europe. Therefore, the structure had to meet the requirements for (northern) European climatic conditions.

The main idea behind the project was to propose a low-cost, lightweight and easily constructed house for refugees, made of paper-based products. However, the system can be also implemented as an alternative to houses with a medium lifespan, social housing, garden sheds, house extensions, summer houses, temporary offices, showrooms, festival offices, cafeterias, etc.

The structural system employed in the proposal was a column-and-beam system. The frame structure was made out of L-shapes and the wall panels were made out of cardboard honeycomb panels. The house should be easy to build, without any need for special equipment and/or professional construction workers.

The House of Cards is a prototype of a house 70 percent of whose volume consists of paper components.

§ 7.5.2 Project concept

The House of Cards is a temporary house designed for asylum seekers and refugees as well as homeless persons. It was designed to be used in European climatic conditions.

The House of Cards is the third generation of the TECH (Transportable Emergency Cardboard House) projects. Based on previous attempts, several details were improved, including the structure of the roof, the foundations, the wall panels, the connections between the elements, the size and the impregnation methods used.

The structural system used in the House of Cards is called FLe^2XARD.

FLe^2XARD is an innovative and flexible building concept for houses with a short and medium lifespan (up to twenty years). The system allows users to combine and arrange functional spaces in a flexible manner and offers an affordable, sustainable and adequate accommodation solution.

The basic structural system consists of prefabricated cardboard panels and a cardboard frame structure. The frame provides the structure with added stability and strength. The houses are installed on an elevated floor made of prefabricated slabs levelled by means of ground screws or blocks of concrete. The building process, using prefabricated elements, is fast and easy. The elements do not weigh much, do not take up much storage space and can be easily transported.

FIGURE 7.44 TECH 03 , visualisation

The proposed solution allows different users to choose different types of houses with various functions and various sizes.

There are two basic units, which can be clustered in order to create different configurations (see Figs 7.45 – 7.46).

The smallest units, with a usable area of 12m² or 25m², are designated for singles or couples. A combination of one smaller and two bigger units provides a comfortable space for two big families (ten persons) or eight individuals. A spatial arrangement with an atrium (see Fig7.47) can be used by three families. Alternatively, the buildings can be arranged in a row of houses which can house twelve people (see Fig. 7.48)

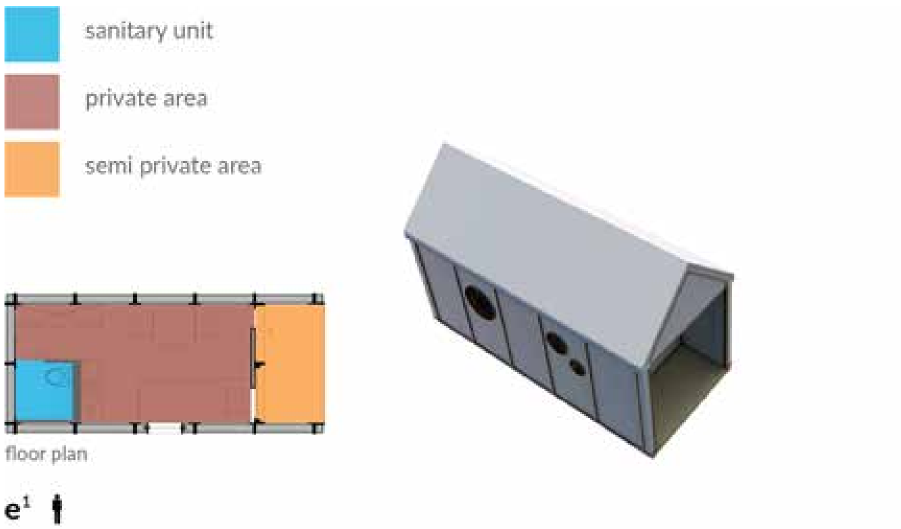

FIGURE 7.45 e^1 unit

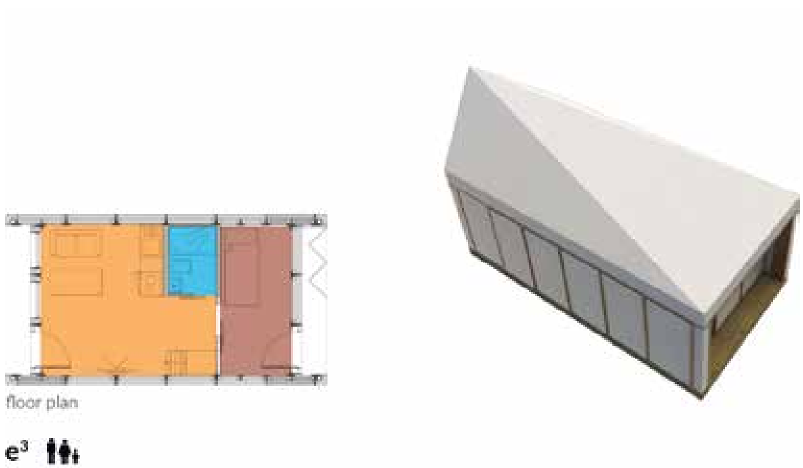

FIGURE 7.46 e^3 unit for one family

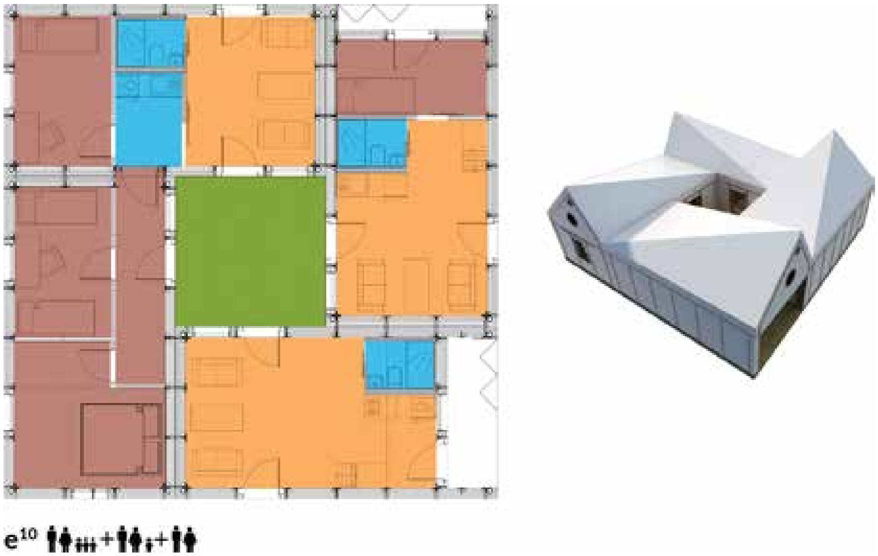

FIGURE 7.47 e^{10} for three families

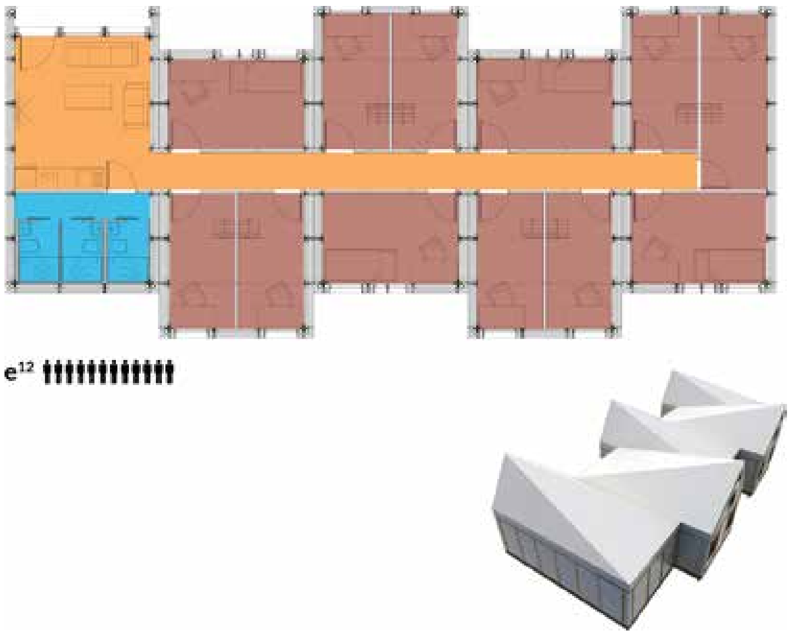

FIGURE 7.48 e^{12} for thirteen individuals

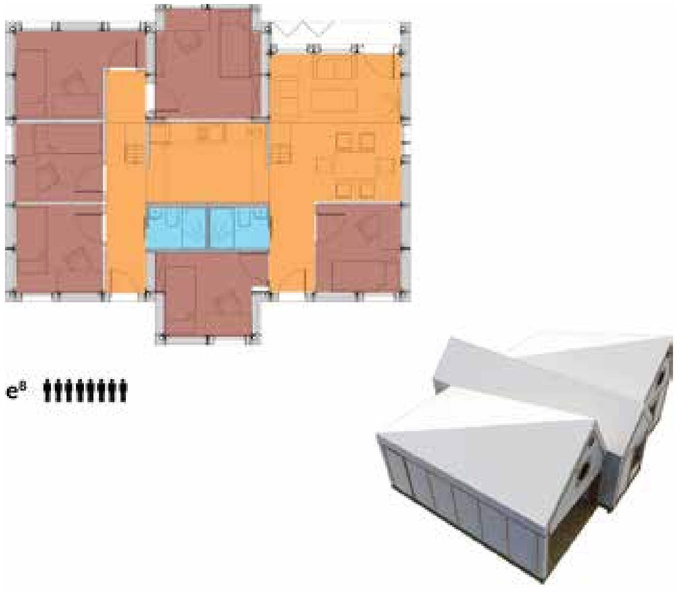

FIGURE 7.49 e^8 for eight individuals

FIGURE 7.50 e^{12} for thirteen individuals

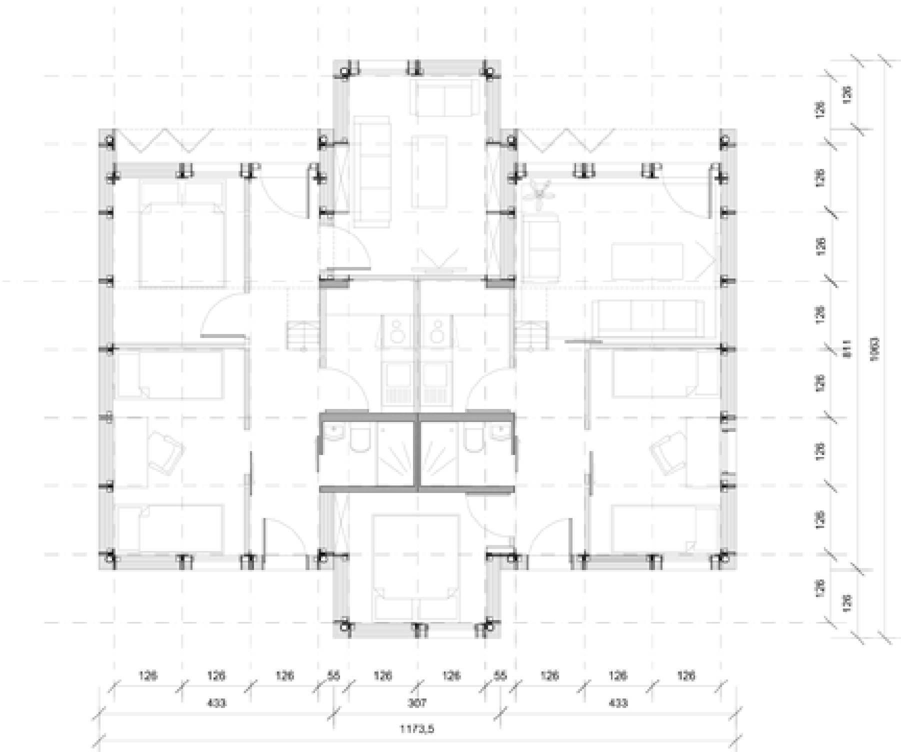

FIGURE 7.51 e^{10} for 10 people, 2 families, plan view

The houses look modest, but cover every basic need. The inclined shape of the roof minimises the heatable volume of the house and simultaneously serves as a passive ventilation system. The mezzanine can be used for storage or as an extra bedroom.

The project was kept sustainable by using cardboard as the main building material. Cardboard is recyclable and low cost, especially when it is mass produced. Cardboard has been proved to be a suitable building material in many projects – not just projects involving temporary housing, but projects involving structures for permanent use. The wall panels of the FLe2XARD system are composed of honeycomb cardboard panels covered with water and moisture barriers: polyethylene film on the inside and PVC foil on the outside. Cardboard treated with fire-retardants will be sufficiently fire-resistant to meet the fire code requirements for small buildings (EW30). Honeycomb panels can be filled with cellulose thermal fibres to achieve a U-factor of up to 0.21 W/m^2K, which makes the units energy-efficient and reduces the operational costs. Thanks to the small size and low weight of the panels, the units can be erected by two persons using only very basic equipment. The FLe2XARD panels are fixed to the frame in a way that allows users to replace or remove them anytime, which makes the concept highly flexible.

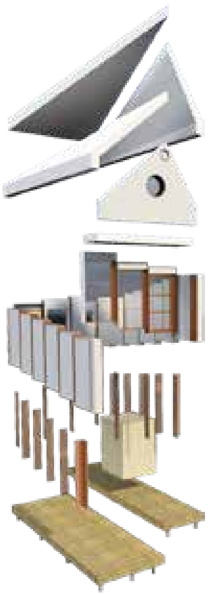

FIGURE 7.52 e^3 exploded geometry

FIGURE 7.53 e^3 axonometric view

Depending on the amount of space available, the houses can be placed between existing buildings or grouped together in bigger constellations. Two possible arrangements of several houses are proposed: a ‘nest’ for smaller groups of fifty people (E50) or a compound for up to five hundred people (E500). It is advisable to place the houses in such a way that they form a courtyard, a place to meet and undertake activities together. This will increase the community spirit among the people living in the group.

Once the houses are no longer needed, they can be easily dismantled and recycled. The FLe2XARD can be (re)used for housing people such as refugees, students, holiday-makers or festival attendees. The system can also be applied to weekend cabins at campsites or in garden plots.

FIGURE 7.54 E^{50} spatial layout for 50 people

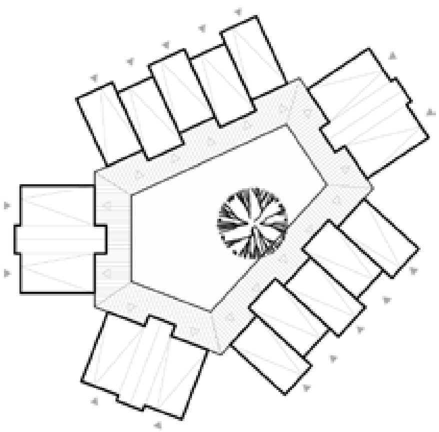

FIGURE 7.55 E^{50} spatial layout for 50 people

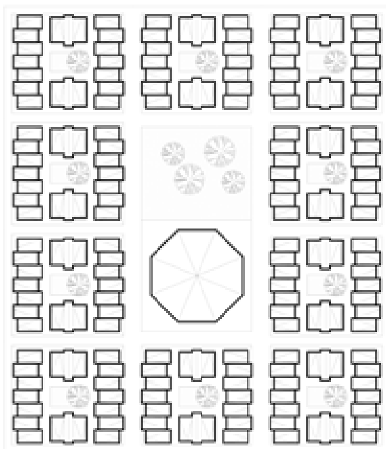

FIGURE 7.56 E^{500} spatial layout for 500 people

§ 7.5.3 Technical and material solutions

The building process of TECH 03 was divided into several phases, and some parts were prepared simultaneously. A team of ten students was involved in the preparation and the constructions work. The building consisted of several types of components: a floor with feet, a frame structure, wall and roof panels, and a front wall.

The floor and feet were prepared as one component made out of timber. Timber beams measuring 14 x 14cm were screwed together and formed a base frame. 14 feet made out of timber blocks measuring 14 x 14cm were screwed to the bottom of the frame. Inside the base frame were intermediate planks designed to support 18mm plywood floor panels. The base frame and wall and the roof frame system were connected to each other by means of 18mm plywood board. This board also protected the wall panels from damage at the floor level, e.g. damage caused by the impact of kicks, balls, etc. The floor panels were able to be opened to facilitate installation of water supply and sewage.

The frame structure of TECH 03 was made of paperboard L-shapes. Two of them were glued together to form a T-shaped beam or pillar. The pillars were erected on the base frame beams and were connected by an 18mm board at the base. Screw connections helped keep the base board, T-shaped pillar and wall panel together at the bottom.

The connectors between the pillars and rafters were made of wood. The flanges of the T-shaped pillars and rafters were encased by double-layered plywood joints and bolted in place. A similar connection was used between the rafters. The frame was connected to the wall panels by means of wood screws. All the connections were preset and the holes in the frame structure were made prior to impregnation.

The wall and roof panels consisted of three laminated honeycomb cardboard panels 50 mm thick. The panels came in a standard size, 1200x 2400mm, and did not need a size adjustment, which meant that very little material was wasted. The outer and inner panels were coated on one side with polyethylene film. The other sides were covered with 300 g/m^2 Kraftliner paper. The middle panel was covered with Kraftliner paper on both sides to improve the performance of the lamination.

The roof panels were cut at a certain angle to ensure that they fit at the top of the roof and at the connection with the walls.

The front wall consisted of a cardboard frame and a polycarbonate window and door. The frame was connected with the intermediate base beam by means of 18mm board.

The polycarbonate panel was connected to the frame with screws. The door was made out of 6mm plywood filled with one 50mm honeycomb panel.

The windows consisted of a frame made of paper tubes, Plexiglas and timber joinery. The paper tubes, whose dimensions were 200mm, 400mm and 700mm, were specially impregnated.

FIGURE 7.57 Floor component

FIGURE 7.58 Frame structure

FIGURE 7.59 T-shape pillars consisting of two L-shapes laminated together

FIGURE 7.60 Timber connectors between pillars and rafters

FIGURE 7.61 Wall panel

FIGURE 7.62 Window frame

§ 7.5.4 Prototyping

The prototype of TECH 03 was built during the Summer School of Architecture Living Unit in 2016. The theme of the Summer School referred to the need for emergency shelters that can be easily transported and can serve homeless people, victims of natural disasters and forcibly displaced people. In addition to the House of Cards, four prototypes of shelters were built. More information about the Summer School can be found on www.ssa.pwr.edu.pl.

The realised prototype of the House of Cards is the smallest unit of the Flexard system. The usable area of the house is 12m², plus a veranda measuring 2.3 m². A prototype was built and exhibited in the Wroclaw city centre in Poland. Later the unit was moved to the campus of Wroclaw University of Science and Technology's Faculty of Architecture for further testing.

The unit was prefabricated in a production hall. The partially assembled structure was then transported to the Wroclaw city centre, where the roof structure and panels were installed.

The House of Cards is powered with photovoltaic panels and lit by means of LEDs. Its battery allows it to use lights for up to 48 hours in bad weather conditions.

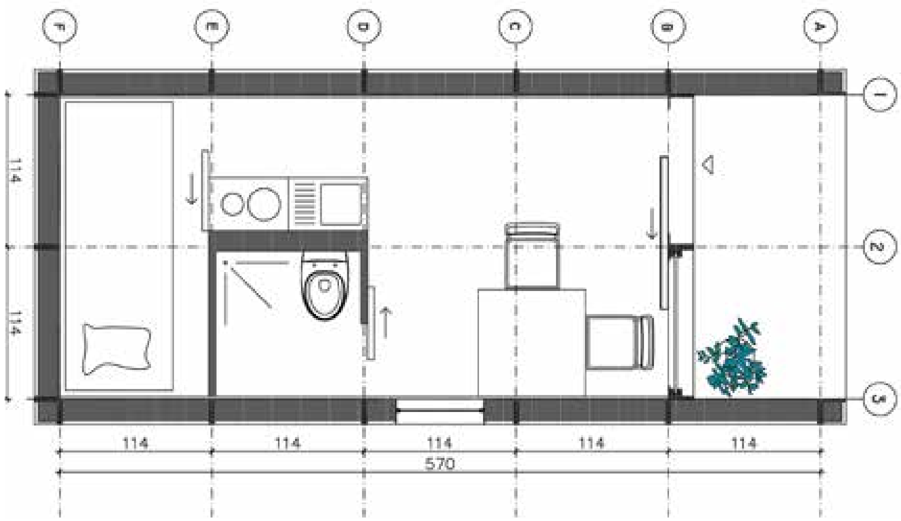

FIGURE 7.63 The House of Cards prototype plan

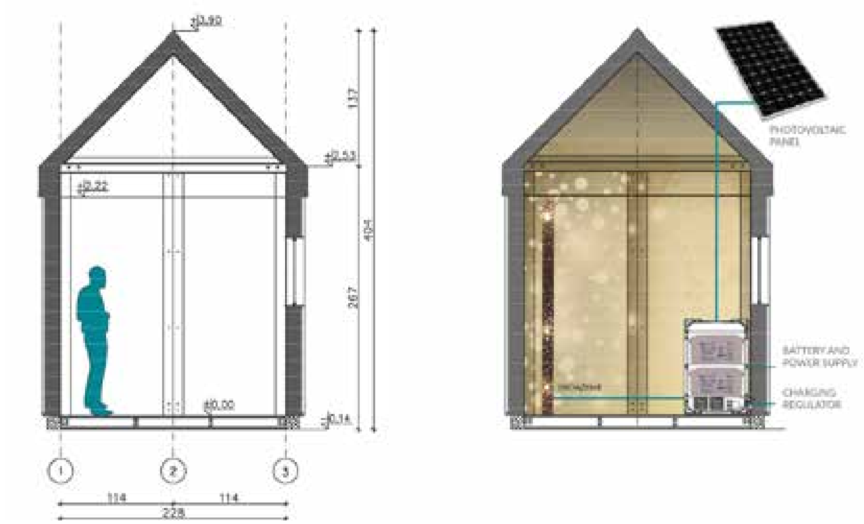

FIGURE 7.64 The House of Cards section and FV ionstallation

FIGURE 7.65 Construction of the prototype

FIGURE 7.66 Constraction of prototype- wall with large window

Impregnation

Two different ways of impregnation were used in the TECH 03 prototype. The first was coating the structural frame elements. The second was laminating the wall and roof panels with PVC foil. The honeycomb cardboard panels which constituted the wall and roof panels were additionally coated with polyethylene film during production of the facing layer. Frame elements made of full board L-shapes laminated together were painted with polyurethane varnish on the outside (the side that was in direct contact with the wall panels) and were painted with a lighter type of paint normally used to impregnate concrete elements. The products were suggested by the partner of the project company, PPG. For additional impregnation, the outer edges of those paper tubes that were used as a window frame and the ends of the T-shaped beams were coated with a product which turned into a thick rubber layer after application.

FIGURE 7.67 Impregnated window frames

FIGURE 7.68 Impregnated T-shaped structural frame elements

The house was ventilated by means of a ventilation grid placed at the high point of the rear gable wall and the gap under the door in the opposite wall. There was one window that could be opened.The power installation was composed of three photovoltaic panels, a battery and LEDs.

FIGURE 7.69 the House of Cards on campus of Faculty of Architecture, Wroclaw University of Science and Technology

FIGURE 7.70 the House of Cards at Solny Square

FIGURE 7.71 Night view

FIGURE 7.72 Interior of the House of Cards

FIGURE 7.73 Side wall

FIGURE 7.74 Top view on the House of Cards, Wroclaw 2016

§ 7.5.5 Evaluation

The prototype of TECH 03 was built in a production hall, then transported by a low-bench truck to Solny Square in Wroclaw, where it was exhibited there for two weeks. Afterwards it was transported to the campus of the Faculty of Architecture.

After one year's worth of exposure to natural conditions, the structure remains stable. It was subjected to strong winds, rain and snow, as well as to low and high temperatures. Between 10 October 2016 and 10 October 2017, the most extreme weather conditions recorded in Wroclaw were as follows: [10]

- The lowest temperatures were -10°C in January and -5°C in February.
- The highest temperatures were 34°C in July and 36°C in August.
- The strongest winds measured were 60km/h in November, 65 km/h in January and 65 km/h in the first half of October 2017.
- The highest level of relative humidity recorded was 85% in December and 90% in February and May.
- The highest rainfall level was 20mm in April and July, and 22mm in September.

Some parts of the envelope of the building were slightly damaged by the rain and high humidity. The windows frames and the adjacent parts of the wall panels, in particular, were soaked. The structural frame seems to be intact and together with the wall and roof panels, it remains a stable system. The structure was left unused for an entire year, meaning there was no heating, which definitely contributed to the damage caused by the high humidity inside the building.

It can be concluded that the TECH 03 structure proved stable and suitable for natural conditions in Europe, where there is a 46-degree temperature range during the year (-10°C to 36°C) and relative humidity may be as high as 90%.

The next step will be to dismantle the structure and to recycle its parts. This will provide important information that will help us estimate the environmental impact and recyclability rate of the building.

§ 7.6 Conclusions

The various projects involved in the Transportable Emergency Cardboard House (versions nos. 1-3) presented a possible solution for emergency architecture composed of paper-based elements and components. The goal of the projects was to come up with a structural system that is suitable for emergency situations. In other words, it had to be low-cost, easy to transport and easy to build, even without specialist tools and professional construction workers. Paper-based products were used as an alternative to traditional materials such as timber, aluminium or plastics. The idea was that the building elements and components should be able to be recycled after the lifespan of the structure.

TECH was a concept for a shelter designed for victims of natural and man-made disasters and for homeless persons.

TECH 01 was designed as a replacement for the typical UNHCR family tents. The first version of the Transportable Emergency Cardboard House was designed for refugees living in the camps of northern Iraq. During the 2014-2015 winter, many locally built tents collapsed due to snowfall. TECH 01 is an emergency shelter that provides better thermal insulation and living conditions than tents. Its structure is basic and minimalist. The wall and roof panels were integrated with load-bearing frames. This reduced the construction time, but at the same time it affected the thickness and thermal insulation of the envelope of the building. The usable area of TECH 01 is 17.4m². The costs of TECH 01 were estimated to be €5,000 at most, and its lifespan was estimated to be up to five years.

TECH 02 was a proposition for a temporary shelter or temporary house, also intended to be used in northern Iraq. The shape of the building was determined by the chosen passive-energy solutions, such as a Trombe wall, a tropical roof with a Venturi effect and an under-floor air delivery system. The usable area was 13m². The structural system consisted of T- and X-shaped beams and wall panels. After several days' exposure to the elements, the prototype was demolished and recycled. The estimated costs of this type of shelter were €10,000 to €12,000.

TECH 03 was designed as a temporary shelter or temporary house for asylum seekers, refugees and homeless people. The lifespan of the house was estimated to be five years. The structural system used in TECH 03 was called FLe2XARD and consisted of frame structure elements and wall and roof panels. The frame structure consisted of T-shapes, which were made out of two laminated L-shapes. The system was flexible and allowed designers to create different layouts, depending on the function of the shelter. The system could be used as a house for asylum seekers in asylum seeker centres or in refugee hotspots in Italy and Greece. Alternatively, it could be used as a temporary house for refugees who have been granted refugee status and are all living together in one community. Like the training house, the FLeXARD would be able to support aid organisations in their fight against homelessness. The prototype of the smallest unit of FLe2XARD system was called the House of Cards and had a usable area of 12m² plus a veranda measuring 2.3m². The estimated costs of one unit were €15,000 to €20,000.

The shape of the structures resulted from local environmental conditions. TECH 01 was a simple house with a double pitch roof at an angle of 12°. TECH 02 had a more complicated roof structure, whose shape was determined by the need for a tropical roof and the Venturi effect.

Mass-produced products produced by paper manufacturers were used in each of the TECH projects. Only the floors and joints were made of timber. The rest of the buildings was made of paper. In TECH 01 structural panels were designed. These panels incorporated a structural frame, connection elements and an insulating envelope. TECH 02 featured a wall structure made of T and X-shaped pillars and beams. The roof structure was made out of U-shapes. The wall and roof panels provided the frame structure with additional stiffness but did not carry any substantial loads. They were made out of laminated honeycomb panels and corrugated cardboard. In TECH 03 the whole frame structure was made out of T-shapes consisting of two laminated

L-shapes. The wall and roof panels were made out of laminated honeycomb panels. The combination of T-shaped pillars and beams helped eliminate thermal bridges. It also made the structure easy to understand and intuitive. All the wall panels had the same dimensions. These dimensions were identical to the standard dimensions used by the paper industry, which would have a positive effect on the price of the product. The lightweight photovoltaic panels installed in TECH 02 provided the minimal amount of energy needed to light the interior.

In order to research TECH's potential for series production, a SWOT analysis was performed.

STRENGTHS	WEAKNESSES
1. readily available, low-cost, mass-produced elements 2. recycled and recyclable 3. good insulation properties 4. flexible functional arrangement 5. simple and intuitive structure 6. lightweight and limited in size	1. vulnerable to water and humidity 2. irregular quality of paper-based elements (depending on source material) 3. impregnation reduces eco-friendliness 4. limited size of the structure 5. limited lifespa
OPPORTUNITIES	**THREATS**
1. when there is a demand for a large number of emergency shelters and houses 2. development of paper industry 3. growing environmental awareness 4. potential for commercial applications	1. competitors 2. lack of legal regulations with regard to paper as a building material 3. users have little faith in paper 4. improper use

TABLE 7.3 SWOT analysis

	O1	O2	O3	O4	T1	T2	T3	T4
S1	++	0	+	++	++	0	0	0
S2	0	0	++	++	+	0	0	0
S3	++	0	++	+	+	+	++	0
S4	++	0	0	++	+	0	0	+
S5	++	0	0	++	++	+	+	++
S6	+	0	+	++	++	0	0	++
W1	+	0	0	+	+	++	++	++
W2	++	0	0	++	+	++	++	+
W3	+	0	++	+	0	+	+	+
W4	+	0	0	++	++	++	+	0
W5	++	0	0	++	++	++	++	++

TABLE 7.4 SWOT analysis matrix

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 further the 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 positively effect on people's faith in paper as a building material. The flexible layout of the units can be adapted to suit varied 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 TECH is paper's vulnerability to water and humidity. Existing solutions such as tents and containers, made of plastics or metals, are completely watertight. This vulnerability to water will likely cause users and local authorities to have limited faith in TECH. Damage caused by TECH 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 without 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.

The above analysis shows that paper products can be used as a building material for emergency shelters and houses, as long as its limitations are respected.

The strength of the project lay in its simple structural system, which could be managed even by unskilled workers. Other strengths were the standardised building elements and components, and the building's functional flexibility. The building components were lightweight and easy to transport. However, the system may not be able to be implemented in certain countries due to a lack of legal regulations. Commercial realisations of the concept would probably result in further research on the shelter system, which would be useful.

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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%.

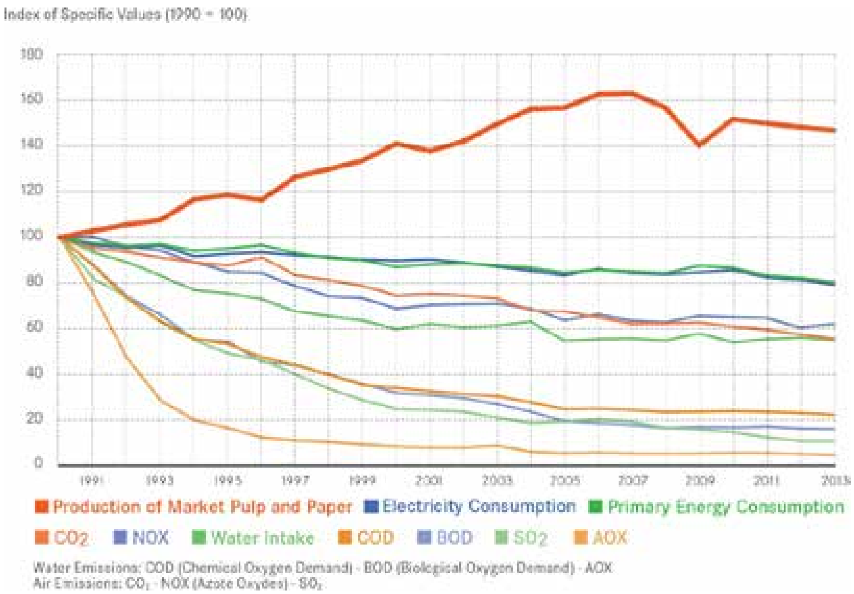

FIGURE 8.1 Evolution of Environmental Impacts of the CEPI Pulp and Paper Industry

§ 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/M²)
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/m² °C
Aluminium facing	Aluminium alloy layer 1 mm, glue, corrugated cardboard core 100 mm, glue, aluminium alloy layer 1 mm	0.9 W/m² °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/m² °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/m² °C
Brick wall, Swiss module	Brick 200 mm	2.20 W/m² °C
Lightweight concrete wall	Lightweight concrete blocks 200 mm	0.95 W/m² °C

TABLE 8.4 Comparison of cardboard composite sample vs. conventional samples (per 1m²) [7]

Comparison of cardboard composite sample versus conventional samples (per 1m²) [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/m²K	203.5mm	156mm
Sample 2 3mm cardboard, seven 25mm honeycomb cardboard panels 3mm cardboard	0.2180 W/m²K	203.5mm	181mm
Sample 3 3mm cardboard 3mm cardboard, eight 25mm honeycomb cardboard panels, 3mm cardboard	0.1915 W/m²K	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/m² °C
- U-value (floor) 0.79 W/m² °C
- U-value (roofing) 4.63 W/m² °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/m² °C
- U-value (floor) 0.39 W/m² °C
- U-value (roofing) 0.32 W/m² °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/m² °C
- U-value (floor) 2.31 W/m² °C
- U-value (roofing) 5.15 W/m² °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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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.

TOC

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.

TOC

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.

Appendix

On 23 March 2015 ir. Peter Eigenraam and the author of this dissertation conducted material tests under the supervision of Dr Fred Veer. The tests were carried out in the laboratory of TU Delft's Faculty of Mechanical, Maritime and Materials Engineering.

The tested elements were paper tubes, rectangular in section, whose dimensions were 58x68.5mm. The tubes consisted of two cardboard U-shapes glued together with 'Bison' wood glue. Each element measured 55x63mm, and its wall was 5.5 mm thick (see Fig. APP.1). The U-shapes were made of recycled cardboard.

Five specimens were tested for bending strength and five specimens were tested for axial compression strength.

The specimens used in the compression tests were 300mm long.

The tests demonstrated that all the specimens behaved similarly.

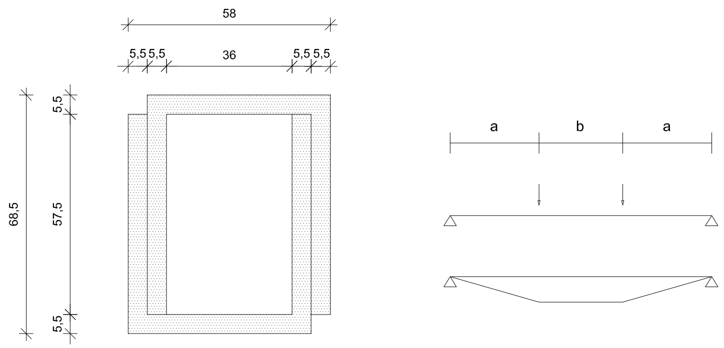


FIGURE APP.1 Paper tubes test on bending and axial compression at TU Delft, bending test scheme

Bending tests

Bending tests were carried out by using a four-point bending with continious rate of deformation.

The specimens used for the bending tests were 1,080mm long. The support points were equidistant: 255mm from the sides and 240mm between the middle points (see Figs. APP.1, APP.2 and APP.3).

The results of this specyfic tests showed that rectangular tubes can bear up to 1,500 N before the material is damaged and wrinkles begin to appear. Deflection was observed at a speed of 10mm per minute. After the critical point (approx. 1,500 N) the material became weaker, and without any extra forces it deflected up to 50mm when the test was stopped. The maximum level at which the element can be safely bent was 1,400 N (140 kg) (see Fig. 2.41).

After the bending test, the permanent deformation of the elements, compared to the original specimen, was 15mm.

FIGURE APP.2 Paper tubes tested on bending at TU Delft

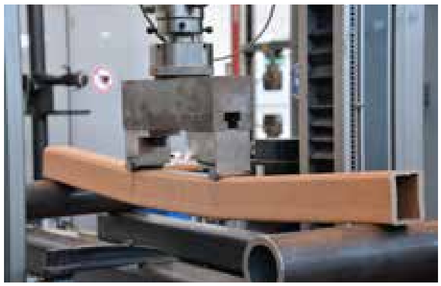


FIGURE APP.3 Paper tubes tested on bending at TU Delft

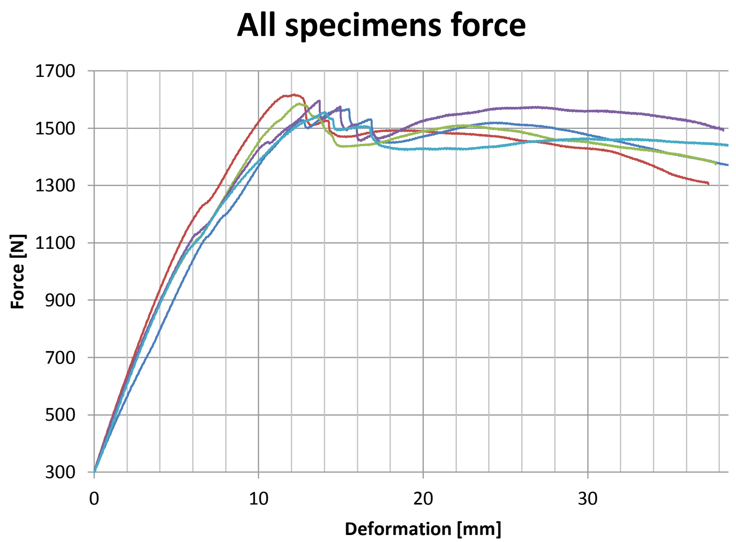


FIGURE APP.4 Stress – strain curve for the bending tests of rectangular tubes conducted at TU Delft – Specimens 1-5

As the above graphs shows, all five specimens have similar strength properties for bending.

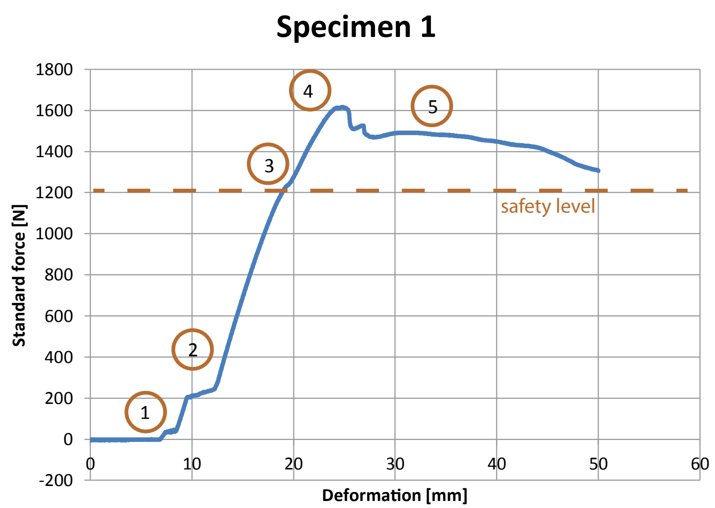


FIGURE APP.5 Stress – strain curve for the bending tests of rectangular tubes conducted at TU Delft – Specimen 1

Specimen 1 Max F [N] = 1616,954

The graph representing the tests conducted at TU Delft shows five different stages of material behaviour (see Fig. APP.5).

1 Little or no force is applied to the specimen and some deformation can be seen. This is the stage when material is aligned to the machine plates. This stage can be dispensed with in respect to material behaviour in the structures.

2 Forces applied to the specimen are represented by a linear graph of the deformation. These forces reach a certain level at which the first wrinkles occur.

3 The material is now slightly damaged but afterwards the deformation is still linear. Wrinkles can be observed at the top of the specimen. Some primary failures occur under compression.

4 Failure in compression. The top of the specimen is wrinkled, but the material continues to resist to the applied force.

5 Falling and gaining. The specimen is slowly losing its strength but the graph shows that the loss of strength is not immediate. However the load applied by the testing machine fluctuates. After the specimen shows some weakness, the forces are decreased, then increased again. At this stage some more wrinkles appear at the top of the specimen, which means that the compression forces at the top are changing the arrangement of the layers of cardboard. This is typically how paper behaves when local buckling appears, but it does not destroy the whole specimen. Continious buckling behaviour slowly decreases the strength of the specimen, but it can still withstand a certain amount of force.

Five specimens were tested for bending moments. The lowest observe test was 1,550 [N] and the average was 1,583 [N].

- Specimen 1 Max F [N] = 1617,0
- Specimen 2 Max F [N] = 1566,4
- Specimen 3 Max F [N] = 1585,9
- Specimen 4 Max F [N] = 1595,4
- Specimen 5 Max F [N] = 1555,0

AVERAGE F [N]: 1583, 9 [N]

SAFETY LEVEL F [N]= 1400

During design the maximum allowable value most be chosen to ensure the structure safety.

The average strength for bending was equal to 1538, 9272 N, which could be assumed as 1500 N and safety level for bending should not exceed 1400 N

The strength of the tubes may vary, depending on the quality of the material and the source material of the pulp. It is advisable to check each set of products provided by the manufacturer before using it in the building industry, by checking one to five specimens randomly selected from the set.

At lowest measured force:

$I = I_{out} - I_{in}$

$I = 58 \times (68.5)^3 / 12 - (58-11-11) \times (68.5 - 5.5 - 4.4)^3/12$

$I = 983198mm^4$

$W = I/h/2$

$W = 28706mm^3$

$M = F/2 \times a$

$M = 198263Nmm$

$\sigma = M/W$

$\sigma = 6.9\ N/mm^2$- stress when the buckling occured

Axial compression tests

Axial compression was tested on five specimens at a speed of 20mm per minute and a maximum compression deflection of 100mm. There were five specimens, each of which was 300mm long (see Figs. APP.6 and APP.7).

The results shows that rectangular tubes made out of two cardboard U-shapes can bear up to 16,000 N.

After the compression test, the difference between the original specimen and the tested one was 75mm. This means that after the material had been subjected to a 100 mm compression test, there was a permanent deformation of about 75mm (see Fig. APP.7).

The strain was $\varepsilon = \Delta L/L = 75/300 = 1/4$ [-]

The important information gleaned from this test was the strength of the glue, which did not tear apart during the tests.

The level of the moisture as well as temperature in the room might have significant influence to the material properties.

FIGURE APP.6 Paper rectangular tubes tested on compression at TU Delft

FIGURE APP.7 Paper rectangular tubes tested on compression at TU Delft

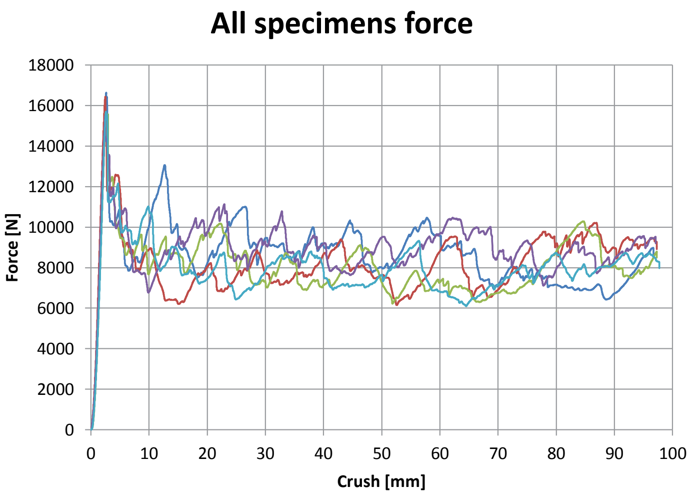


FIGURE APP.8 Stress – strain curve for the axial compression tests of rectangular tubes conducted at TU Delft – Specimens 6-10

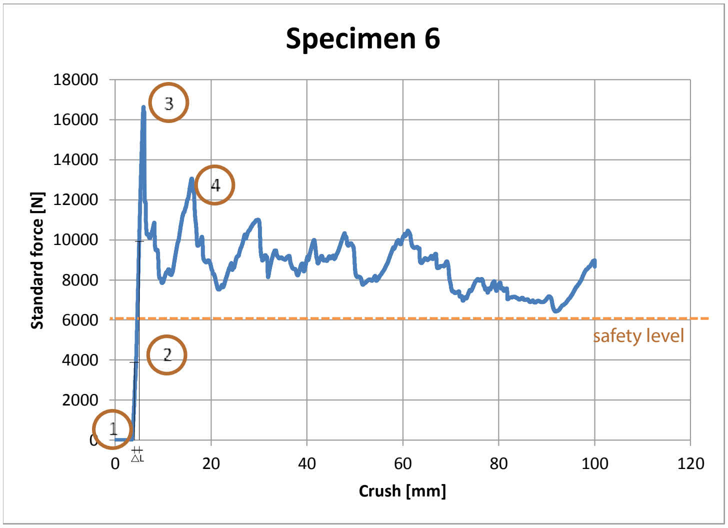


FIGURE APP.9 Stress – strain curve for the axial compression tests of rectangular tubes conducted at TU Delft – Specimen 6

Specimen 6 Max F [N] = 16624,07

Presented below are four characteristic stages in material behaviour during the compression tests (see Fig. APP.9):

1 The first stage is when the material is placed in position, little to no force is applied and the specimen is aligned to the benches of the machine.

2 Linear deformation

3 Failure load, end of elastic strain – stress behaviour of the material. This is the point where the specimen first sustains damaged. Wrinkles are observed in the material. The wrinkles occur at the top and bottom of the specimen. This is because of the imprecise cut of the element. It can be assumed that no cardboard element will ever be cut extremely precisely, and that wrinkles will occur at one of its ends. This information is important for the future observations of paper structures.

4 Failing and gaining strength. This part of graph is very interesting in that it shows that the tested elements gain strength after first having been weakened. In other words, even if the material is subjected to forces that approach its maximum load point, it will not collapse at once, but will slowly shrink, and wrinkles will appear.

The orange line represents a safety value for constant compression forces (in this case set on 6,000N). Due to the behaviour of the material even after the forces applied exceeded the critical point, caused by sudden load like heavy snowfall or the impact of a car, the material will keep its compressive strength even beyond the safety line.

- Specimen 6 Max F [N] = 16624,1
- Specimen 7 Max F [N] = 16437,5
- Specimen 8 Max F [N] = 15568,7
- Specimen 9 Max F [N] = 15465,4
- Specimen 10 Max F [N] = 15691,2

AVERAGE F [N]: 15957,4

Safety F [N] = 6,000, which is about one-third of max F

The average strength for compression is equal to 15,957.364 N, which can be assumed to be 15,000 N (see Fig. APP.9).

A= 18,7 cm^2 = 0,00187 m^2

Pmax = 8,53 MPa

Fmax= 1627,20 [N]

Young's modulus

Young's modulus is calculated on the basis of the data obtained from Specimen no. 6's compression test, but as is clear from the graph of all specimens combined, Young's modulus in the elastic stress-strain part of the graph can be assumed to be the same for all specimens tested.

$\Delta F = F_2 - F_1$

$= 10002 - 3997$

$= 6005$ N

L = 300mm

$\Delta L = L_2 - L_1$

$= 4.12 - 3.38$

$= 0.74$mm

$A = A_{out} - A_{in}$

$= 58 \times 68.5 - (58 - 11 - 11) \times (68.5 - 5.5 - 5.5)$

$= 1903 mm^2$

$E = (\Delta F \times L) / (\Delta L \times A)$

$= (6005 \times 300) / 0.74 \times 1903$

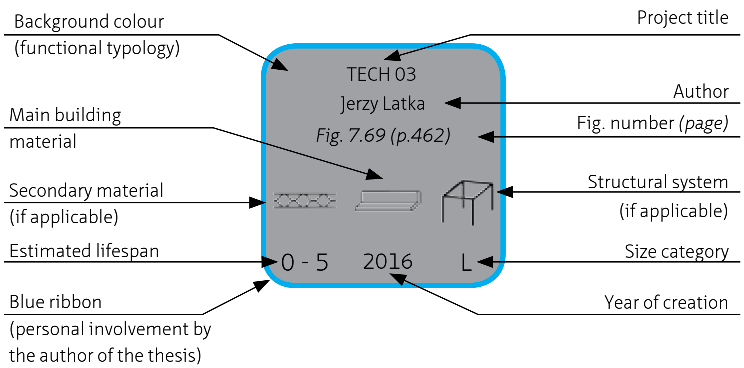
$= 1279 N/mm^2$

= **1.28 GPa**

Young's modulus as obtained in these tests slightly differs from the test results obtained by Shigeru Ban, which ranged from 1.57 GPa to 2.36 GPa. In considering the differences between these test results, the source of the material should be taken into account. All the specimens tested at TU Delft were made from fully recycled material.

Index

One hundred and twelve projects are described in this dissertation. The projects presented in this dissertation were all made out of paper materials, or paper products were used as a main structural element. The projects represented every functional category presented in Chapter 3 and came in different sizes. They also differed in terms of their lifespan. The index presented below was prepared in order to organise existing knowledge of paper in design and architecture. The projects were divided according to the type of material used: paper (or paperboard), paper tubes, corrugated cardboard, honeycomb panels and cardboard U- and L-shapes. Inside these categories, the projects were sub-divided according to their sizes (S, M, L, XL). The tiles representing the various projects contain several types of information. At the top, the name of the project and the authors are provided. The next information provided is the number of the image and the page on which the project is described. The next row consists of three icons. The icon on the left presents the secondary material (if a paper-based material was applied); the icon in the middle presents the primary building material, and the icon on the right presents the structural system (where applicable). Three main structural systems were taken into account: a rod structural system, a panel or plate system and a shell system (see Section 4.4.2). At the bottom of each tile there is an estimated lifespan of the product (if known), its year of production and its scale. The background colours refer to the function of the product. A white background means that the project was not realised in the form of a prototype. Some projects fall into two categories. For instance, public buildings that were built for local people after earthquakes (i.e. emergency buildings) are listed as public buildings. A blue ribbon around the project means that the author of this thesis was involved in the project as an author, member of the design team or tutor



Background colours that refer to building functions

products for everyday use, furniture

partitions

interior pavilions and ehibitions

exterior pavilions

houses and buildings for privte clients

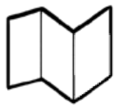
public buildings

emergency shelters

unbuilt

Icons that refer to structural systems


rod structural system


panel or plate system


shell system

Icons that refer to the paper-based materials

paper or paperboard


paper tubes


corrugated cardboard


honeycomb panels


cardboard L-shapes or U-shapes

Icons by Bozena Chadzynska

Business card case
SIWA
Fig. 3.5 (p.120)
0 - 5 2013 S

Traditional Japanese paper lamp
Fig. 3.2 (p.118)
0 - 5 2013 S

Cloth made out of washi paper
Fig. 3.3 (p.118)
0 - 5 unkn. S

Pleated Paper Dress
Issey Miyake
Fig. 3.4 (p.120)
0 - 5 2008 S

Traditional Japanese paper screen
Fig. 3.1 (p.118)
unkn. 2013 S

Shoji and fusuma
Fig. 4.1 (p.166)
13th C S

The Paper House
Elis F. Stenman
Fig. 4.6 (p.168)
0 - 1 1924 S

Dome-shaped House
Container Corporation of Am.
Fig. 4.8 (p.169)
unkn. 1954 M

Plydom
S. Hirshen and S. van der Ryn
Fig. 4.11 (p.170)
unkn. 1966 M

Cardboard House
P. Stutchbury and R. Smith
Fig. 4.72 (p.211)
0 - 5 2004 M

MCT Lamp
HoUE, WUST
Fig. 3.13 (p.124)
0 - 5 2012 S

Muff Puff Seats
HoUE, WUST
Fig. 3.15 (p.124)
0 - 5 2012 S

Chair
Shigeru Ban
Fig. 3.7 (p.121)
0 - 5 1994 S

Rocking Chair Massager
HoUE, WUST
Fig. 3.18 (p.125)
0 - 5 2012 S

La-Ma Table
HoUE, WUST
Fig. 3.14 (p.124)
0 - 5 2012 S

Muff Puff Sofa
HoUE, WUST
Fig. 3.16 (p.124)
0 - 5 2012 S

Paper Partition Syst. No. 3
Shigeru Ban
Fig. 5.17 (p.315)
0 - 1 2008 L

Paper Partition Syst. No. 4
Shigeru Ban
Fig. 5.18 (p.315)
0 - 1 2013 S

LWET
Shigeru Ban
Fig. 5.22 (p.318)
0 - 5 1999 M

Tensegrity dome
Bucky Lab, TU Delft
Fig. 6.129 (p.388)
0 - 1 2015 M

Dome of the Rings
Bucky Lab, TU Delft
Fig. 6.132 (p.388)
0 - 1 2015 M

The Umbrella Shelter
Bucky Lab, TU Delft
Fig. 6.64 (p.360)
0 - 1 2015 M

The HEX Shelter
Bucky Lab, TU Delft
Fig. 6.72 (p.363)
0 - 1 2015 M

Paper Tea House
Shigeru Ban
Fig. 3.41 (p.139)
0 - 5 112 M

Paper Log House
Shigeru Ban
Fig. 4.36Fig (p.186)
0 - 5 1995 M

Wing Shelter
Bucky Lab, TU Delft
Fig. 6.78 (p.366)
0 - 1 2015 M

SCOLP
Bucky Lab, TU Delft
Fig. 6.18 (p.342)
0 - 1 2013 M

Library of a Poet
Shigeru Ban
Fig. 4,21 (p.177)
∞ 1991 M

Training House
Jerzy Latka
Fig. 5.26 (p.321)
0 - 2 2009 M

The Tree D Papervilion
Technoledge, TU Delft
Fig. 3.50 (p.142)
0 - 1 2017 M

Alvar Aalto exhibition
Shigeru Ban
Fig. 4.19 (p.173)
0 - 1 1985 L

Houses for elderly people
Z. Bac, J. Latka
Fig. 3.60 (p.153)
0 - 20 2012 L

Multished
Taco van Iersel
Fig. 6.3 (p.332)
0 - 1 2002 L

Bije(e)nkorf
J. Latka, J. Schoenwalder
Fig. 6.62 (p.156)
0 - 20 2017 L

WUST Pavilion v.1
Jerzy Latka
Fig. 4.118 (p.240)
0 - 1 2015 L

WUST Pavilion v.2
Jerzy Latka
Fig. 4.123 (p.241)
0 - 1 2015 L

WUST Pavilion v.3
J. Latka, WUST
Fig. 4.146 (p.250)
0 - 1 2015 L

Primary School
Cottrell & Vermeulen
Fig. 4.61 (p.199)
0 - 20 2001 M

Paper House
Shigeru Ban
Fig. 4.30 (p.182)
∞ 1995 L

Ring Pass Hockey Club
Nils Eekhout
Fig. 4.58 (p.220)
∞ 2010 L

Project	Designer	Figure	Range	Year	Size
Takatori Paper Church	Shigeru Ban	*Fig. 4.39 (p.187)*	∞	1995	L
Public Farm One	WORK AC	*Fig. 3.58 (p.146)*	0 - 1	2008	L
Paper Nursery School	Shigeru Ban	*Fig. Fig.4.99 (p.228)*	0 - 5	2014	L
KUAD Studio	Shigeru Ban	*Fig. 4.94 (p.225)*	0 - 5	2013	L
Hualin Primary School	Shigeru Ban	*Fig. 4.77 (p.215)*	0 - 5	2008	L
Paper Arch Dome	Shigeru Ban	*Fig. 4.40 (p.189)*	∞	1998	L
Cardboard Cathedral	Shigeru Ban	*Fig. 4.150 (p.258)*	∞	2013	L
Paper Dome	Shigeru Ban	*Fig. 4.68 (p.205)*	0 - 10	2003	XL
Japan Pavilion	Shigeru Ban	*Fig. 4.56 (p.195)*	0 - 1	2000	XL
Nomad System Dividers	J. Salm, R. Allen	*Fig. 3.29 (p.130)*	0 - 5	2013	S
Bloxes	Jef Raskin	*Fig. 3.30 (p.130)*	0 - 5	1960s	S
Taco Wall	Taco van Iersel	*Fig. 6.2 (p.332)*	0 - 5	2002	S
BIA Systeemwanden		*Fig. 3.31 (p.130)*	0 - 5	201	S
Fold a profile	Bucky Lab, TU Delft	*Fig. 6.146 (p.392)*	0 - 1	2015	S
Foldschool	Nicola Stäubli	*Fig. 3.11 (p.122)*	0 - 5	2007	S
Lounge Chair	Zach Rotholz	*Fig. 3.9 (p.122)*	0 - 5	2011	S
Wiggle Side Chair	Frank Gehry	*Fig. 3.7 (p.121)*	0 - 5	1972	S
The Paperpedic Bed	Karton Group	*Fig. 3.10 (p.122)*	0 - 5	2011	S
Wikkel House	René Snel	*Fig. 4.109 (p.234)*	0 - 50	1996	M
Cardborigami	Tina Hovespian	*Fig. 5.19 (p.316)*	0 - 1	2010	M

Self Shading Structure
Bucky Lab, TU Delft
Fig. 6.135 (p.389)
0 - 1 2015 M

Waffle Dome
Bucky Lab, TU Delft
Fig. 6.37 (p.350)
0 - 1 2013 M

Experimental Shelter
Institute of Paper Chemistry
Fig. 4.7 (p.169)
0 - 25 1944 M

Emergency Shelter
California Polytechnic
Fig. 4.15 (p.171)
unkn. 1977 M

Shellter
Bucky Lab, TU Delft
Fig. 6.139 (p.390)
0 - 1 2015 M

Outreach
Bucky Lab, TU Delft
Fig. 6.148 (p.393)
0 - 1 2015 M

Auto-lock Box Dome
Bucky Lab, TU Delft
Fig. 6.36 (p.348)
0 - 1 2013 M

Pappedern
3H Design
Fig. (p.172)
0 - 1 1972 M

BYOH
Bucky Lab, TU Delft
Fig. 6.46 (p.353)
0 - 1 2015 M

Polyhedron-shaped Dome
K. Critchlow and M. Ben-Eli
Fig. 4.12 (p.170)
unkn. 1967 M

Packed
Tom Pawlofsky, ETH Zurich
Fig. 3.56 (p.145)
0 - 1 2010 M

Conci and Ayelt Dome
Bucky Lab, TU Delft
Fig. 4.143 (p.391)
0 - 1 2015 M

The Profile
Bucky Lab, TU Delft
Fig. 6.101 (p.376)
0 - 1 2015 M

Memory Mailbox
HoUE, WUST
Fig. 3.34 (p.140)
0 - 1 2010 M

Cardboard Art House
Papertown
Fig. 3.48 (p.141)
0 - 1 2016 M

Cardboard House
C. Stelt, H. Mesem, W Kahman
Fig. 6.1 (p.332)
0 - 1 1976 M

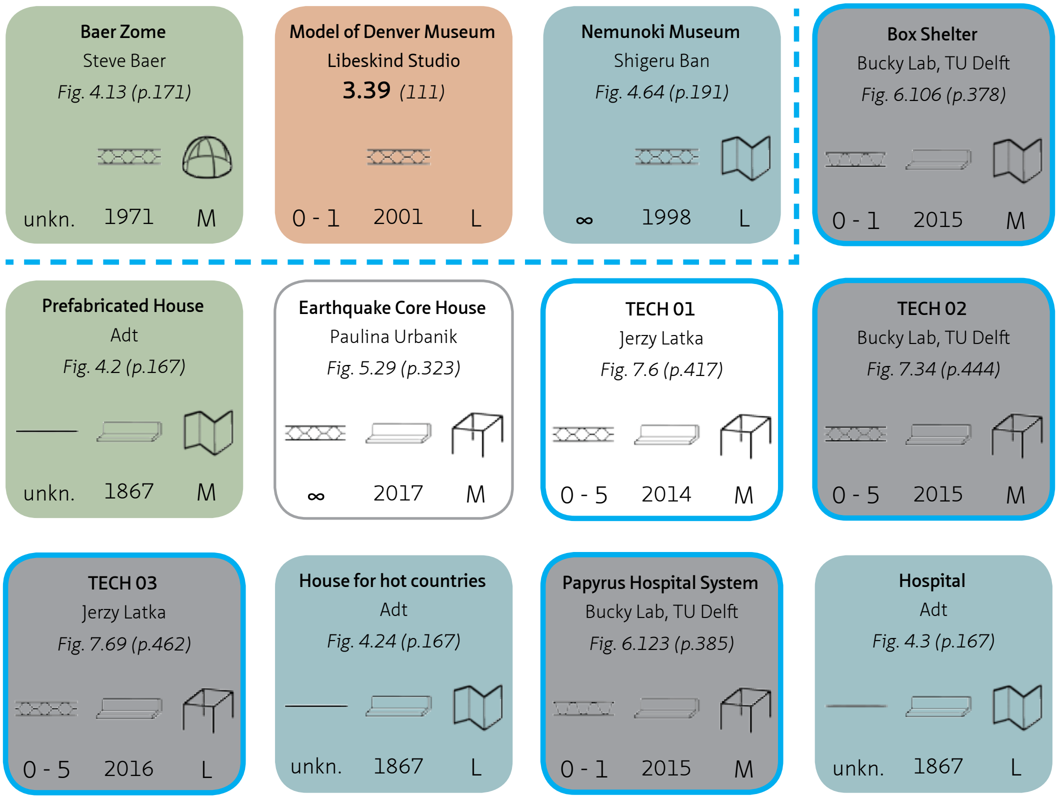
Cardboard Pop-Up Dome
Bucky Lab, TU Delft
Fig. 6.14 (p.339)
0 - 1 2013 M

Cardboard Pavilion
TU Delft
Fig. 6.4 (p.333)
0 - 1 2006 M

Prefabricated Shelter
H. Lee and J. Gibson
Fig. 4.14 (p.171)
0 - 1 1974 M

Platforms of Sound
Zimoun
Fig. 3.45 (p.140)
0 - 1 2014 M

Curved-fold Dome	Bucky Lab, TU Delft	*Fig. 6.22 (p.344)*	0 - 1	2013	M
Dome-shaped Building	Buckminster Fuller	*Fig. 4.10 (p.169)*	unkn.	1957	M
Cowshed-like Structure	Instituut voor Gebouwen	*Fig. 4.17 (p.172)*	unkn.	1975	M
Cardboard Banquette	University of Cambridge	*Fig. 3.54 (p.144)*	0 - 1	2009	L
Apeldoorn Theatre	Hans Ruijssenaars	*Fig. 4.25 (p.180)*	0 - 1	2013	L
Rip Curl Canyon	Ball-Nogues Studio	*Fig. 3.40 (p.138)*	0 - 1	2006	L
Paper Miracle	HoUE, WUST	*Fig. 3.28 (p.129)*	0 - 5	2013	S
UL Lamp	HoUE, WUST	*Fig. 3.6 (p.120)*	0 - 5	2012	S
Kart®on chair	HoUE, WUST	*Fig. 3.20 (p.125)*	0 - 5	2012	S
Lounge L	HoUE, WUST	*Fig. 3.19 (p.125)*	0 - 5	2012	S
Patchwork Armchair	HoUE, WUST	*Fig. 3.17 (p.125)*	0 - 5	2012	S
Landscape Bench	HoUE, WUST	*Fig. 3.22 (p.127)*	0 - 5	2017	S
Work&Roll	HoUE, WUST	*Fig. 3.23 (p.127)*	0 - 5	2017	S
softwall	molo	*Fig. 3.33 (p.131)*	0 - 5	2003	S
Paper Partition Syst. No. 2	Shigeru Ban	*Fig. 5.16 (p.315)*	0 - 1	2005	M
Paper Partition Syst. No. 1	Shigeru Ban	*Fig. 5.15 (p.315)*	0 - 1	2004	M
Cardboard:ception	HoUE, WUST	*Fig. 3.21 (p.127)*	0 - 5	2017	S
Transition House	Fons Verheijen	*Fig. 6.5 (p.333)*	0 - 5	2007	M
Paper Cave	archi-tektura.eu	*Fig. 3.52 (p.143)*	0 - 1	2017	M
Cardboard House	Paul Rohlfs	*Fig. 4.18 (p.172)*	0 - 5	1980	M


Baer Zome
Steve Baer
Fig. 4.13 (p.171)
unkn. 1971 M
Model of Denver Museum
Libeskind Studio
3.39 (111)
0 - 1 2001 L
Nemunoki Museum
Shigeru Ban
Fig. 4.64 (p.191)
∞ 1998 L
Box Shelter
Bucky Lab, TU Delft
Fig. 6.106 (p.378)
0 - 1 2015 M
Prefabricated House
Adt
Fig. 4.2 (p.167)
unkn. 1867 M
Earthquake Core House
Paulina Urbanik
Fig. 5.29 (p.323)
∞ 2017 M
TECH 01
Jerzy Latka
Fig. 7.6 (p.417)
0 - 5 2014 M
TECH 02
Bucky Lab, TU Delft
Fig. 7.34 (p.444)
0 - 5 2015 M
TECH 03
Jerzy Latka
Fig. 7.69 (p.462)
0 - 5 2016 L
House for hot countries
Adt
Fig. 4.24 (p.167)
unkn. 1867 L
Papyrus Hospital System
Bucky Lab, TU Delft
Fig. 6.123 (p.385)
0 - 1 2015 M
Hospital
Adt
Fig. 4.3 (p.167)
unkn. 1867 L

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My PhD journey commenced in October 2009 at Wroclaw University of Science and Technology's Faculty of Architecture, where, upon my graduation, Prof. Zbigniew Bac suggested that I become his PhD student. Two years earlier, together with Prof. Bac, I had founded a scientific students' organisation called 'Humanisation of the Urban Environment'. I would like to thank Prof. Zbigniew Bac for his inspiring lessons about architecture and human-centred design. Prof. Bac, a creator of the idea of 'habitat', which in his understanding is a philosophy that organises human life in the housing environment, rather than designing the space itself, taught me how to deal with architectural design as a complex and multi-layered task. My interest in social design grew from his lessons.

In the year 2012 I was granted one of the greatest opportunities of my life, when I was awarded an EU grant that allowed me to visit Delft University of Technology (also known as TU Delft) as a researcher. At TU Delft, which is a Mecca for students of architecture, I met Prof. Mick Eekhout, who is the Chair of the Product Development department at the Faculty of Architecture. My contacts with Prof. Eekhout inspired me to do more technical research and so to merge my previous human-oriented research with engineering and prototyping. Prof. Eekhout's vast knowledge and insightful comments on my thesis helped me go through the whole process of writing.

My first point of contact with TU Delft was the Bucky Lab course, which is supervised by Dr Marcel Bilow. Since becoming a teacher at Bucky Lab in 2012, I have learnt that in addition to research and all the scientific knowledge I have gained, I was given the opportunity to meet one of the most inspiring people in my life. I am sure now that finishing my PhD research not only helped me get a proper scientific background but also taught me how to be a good teacher, who is demanding but also serves as a helpful and enthusiastic friend to the students.

The year 2013 was another breakthrough in my career. I was fortunate enough to be selected as one of only two international students allowed to do a work placement at Shigeru Ban Studio at Kyoto University of Art and Design. This was my chance to meet my idol. My six-month work placement in Kyoto and Tokyo allowed me to greatly extend my knowledge of paper and the exotic culture of Japan. I will always remember Prof. Ban as a calm, warm and modest person, who is devoted to humanitarian activities but at the same time always on the lookout for innovations and unusual solutions in architecture.

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KCPK KENNISCENTRUM PAPIER EN KARTON

Curriculum vitae

Jerzy Latka, 2017 (photo: Marek Ksiezarek)

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Education

Sep. 2012 – Dec. 2017	**PhD candidate – Paper in Architecture: Research by Design, Engineering and Prototyping – Faculty of Architecture and the Built Environment, Delft University of Technology**
Nov. 2009 – Sep. 2015	**PhD student at the Faculty of Architecture, Wroclaw University of Science and Technology**
April 2013 – July 2013	**research student at Shigeru Ban Studio, Kyoto University of Art and Design**
Oct. 2011 – Sep. 2012	**Master's student at the Faculty of Interior and Industrial Design, Wroclaw Academy of Fine Arts (did not complete degree course)**
Oct. 2002 – Oct. 2009	**Master's student at the Faculty of Architecture, Wroclaw University of Science and Technology**

Professional experience

May 2015 – present	owner – **archi-tektura.eu** – design and research platform for paper in architecture (www.archi-tektura.eu), Wroclaw, Poland; Delft, the Netherlands
Aug. 2013 – Dec. 2013	member of the design and construction team, **Shigeru Ban Architects, Voluntary Architects Network** (www.shigerubanarchitects.com), Tokyo, Japan and Ya'an, China
Dec. 2011 – Aug. 2012	architect assistant, **Sky Project**, Wroclaw, Poland,
July 2011 – Sep. 2011	architect assistant and consul assistant, **Zeev Baran Architect**, Honorary General Consulate of the Republic of Poland in Jerusalem, Israel
Nov. 2010 – May 2011	architect assistant, **Brach Pracownia Projektowa**, Wroclaw, Poland
July 2008 – Sep. 2008	architect assistant, **Adams and Collingwood Architects**, London, Great Britain
July 2007 – Sep. 2007	architect assistant, **ZIP Studio**, Bucharest, Romania
Jan. 2007 – June 2007	architect assistant, **Horn Architekci**, Wroclaw, Poland
Oct. 2005 – March 2006	architect assistant, **OKM Architects**, Galway, Ireland

Academic experience

Nov. 2007 – present	founder (2007), chairman (2007 – 2011) and supervisor (2012 – present) of the scientific students' organisation **Humanisation of the Urban Environment** at the Faculty of Architecture, Wroclaw University of Science and Technology
Oct. 2015 – present	chief organiser of the international **Summer School of Architecture**: Living Unit 2016, Work&Chill 2017
Feb. 2017 – May 2017	teacher of professional practice at **Technoledge course**, Faculty of Architecture, TU Delft
2012, 2014, 2015	design teacher at **Bucky Lab course**, Faculty of Architecture, TU Delft
Feb. 2010 – June 2012	design teacher at **Housing Design** course and **Public Building Design** course, Faculty of Architecture, Wroclaw University of Science and Technology

Memberships

July 2016 – present	International Association for Shell and Spatial Structures (IASS)
Nov. 2009 – present	Organisational Committee of International Conference and Architectural Workshops HABITATY, Wroclaw University of Science and Technology, Poland
Feb. 2017 – Nov. 2017	Committee of the Innovations in Architecture – Architektura Murator magazine
Nov. 2009 – Oct. 2011	PhD Students' Council, Wroclaw University of Science and Technology, Poland

Awards and distinctions

November 2017	finalist of the Blue Sky Young Researchers Europe Award, Confederation of European Paper Industries, Belgium
September 2017	selected as one of the Top Thirty Creative Citizens of Wroclaw, Poland
July 2017	selected as one of top-10 innovators under 35 in Poland by MIT Technology Review, Poland, EU
July 2016	first prize in FUTUWRO competition, part of Wroclaw's 2016 programme for the European Capital of Culture, for the House of Cards project, Poland
November 2015	selected for the New Ideas for the Paper Industry by Confederation of European Paper Industries and European Fibre and Paper Research Organisations, Belgium

Grants and scholarships

April 2014 – July 2015	research on paper as an innovative and pro-ecological building material. Design and realisation of experimental paper pavilion – Mobility Plus grant from Ministry of Science and Higher Education of the Republic of Poland
Oct. 2009 – July 2013	annual scholarship for the best PhD researchers at Wroclaw University of Science and Technology
Oct. 2011 – June 2012	city council's grant for the best PhD researchers of Wroclaw, Poland

List of publications

Journal papers

Latka, J. *ARCHI-TECTURE: paper and cardboard as an innovative material in architectural structures*. Polish Paper Review. 2014, Issue 12, ISSN 00332291

Conference papers

Latka, J. *TECH Transportable Emergency Cardboard House*. Spatial Structures in the 21st Century: Proceedings of IASS 2016 Tokyo Symposium, 26-30 September, 2016, Tokyo, Japan / K. Kawaguchi, M. Ohsaki, T. Takeuchi (eds.). Madrid : International Association for Shell and Spatial Structures (IASS), 2016,

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Book chapters

Bac, Z. Latka, J. *Kibitzes – habitats of the dessert*, Habitats - social architecture / edt. Zbigniew Bac. Wrocław : Oficyna Wydawnicza Politechniki Wrocławskiej, 2014, ISBN 978-83-7493-840-2

Januszewski, W. Latka, J. *Creation of the social space – lessons from Brasillia and Delft* in Habitats: reactivation of small local societies / edt. Zbigniew Bac Wrocław : Oficyna Wydawnicza Politechniki Wrocławskiej, 2016, ISBN 978-83-7493-959-1